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STUDIES ON THE METEOROLOGICAL EFFECTS IN THE UNITED STATES OF THE SOLAR AND TERRESTRIAL PHYSICAL PROCESSES.

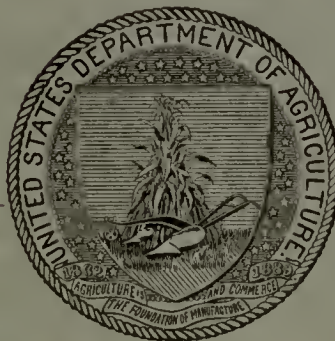
Reprints from the Monthly Weather Review, December, 1902, January and February, 1903.

BY

FRANK H. BIGELOW, M. A., L. H. D.,

PROFESSOR OF METEOROLOGY.

PREPARED UNDER THE DIRECTION OF
WILLIS L. MOORE,
CHIEF U. S. WEATHER BUREAU.



WASHINGTON:
WEATHER BUREAU.
1903.

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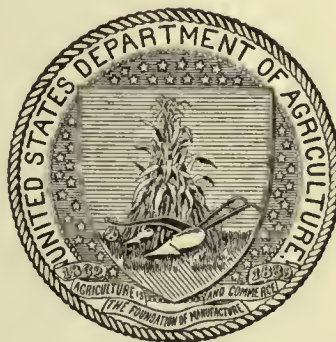
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ERRATA.

Page 33, column 1, description of fig. 26, for "miles" read "meter" in both cases. Page 33, fig. 27, column 2, transpose the legends of figs. I and II, but *not* the numbers.

STUDIES ON THE METEOROLOGICAL EFFECTS OF THE SOLAR AND TERRESTRIAL PHYSICAL PROCESSES.

I.—THE SEMIDIURNAL PERIODS IN THE EARTH'S ATMOSPHERE.

THE DOUBLE AND THE SINGLE DIURNAL PERIODS.

The problem of accounting for the well known semidiurnal periods in the meteorological elements, barometric pressure, vapor tension or humidity, and electric potential, as observed at the surface of the earth, is still awaiting its complete solution, but since additional information on the subject has been obtained in the past few years through the different kinds of observations in the strata at higher levels above the ground, this is sufficient reason for bringing the subject before this section¹ of the American Association for the Advancement of Science. Fig. 1 shows the average curves deduced from the surface observations, as they have been repeatedly made in all parts of the tropical and temperate zones.²

There are two minima and two maxima, the first minimum at about 4 a. m., the second at about 4 p. m.; the first maximum at about 10 a. m., and the second at 8 to 10 p. m. If the sun is supposed to rise and set at 6 o'clock, this indicates that the diurnal atmospheric processes lag several hours behind the hour angle of the sun, just as the seasonal processes lag about forty or fifty days behind the annual temperature changes. Since this retardation occurs chiefly through the slow radiation and convection of the atmosphere, just as the annual temperature wave lags in penetrating the ground through its slow conduction, so therefore, these retardations in the diurnal elements may become the means of calculating the coefficients of conductivity and convection in the air. Now it is to be noted that while the pressure, vapor tension, and electric potential give a decided double period, the diurnal actinic radiation from the sun shows only a small midday depression, and the temperature none at all, for this is a curve with a single maximum at 3 p. m. and a minimum at 4 a. m. This suggests the problem to be resolved, namely, the occurrence of single and double diurnal periods at the same time in the lower strata of the atmosphere.

In past years, before it was recognized that the single period prevails throughout the atmosphere, except in its lowest layers, efforts were made to account for the surface double period in two ways: (1) by referring it to a dynamic forced wave involving the entire atmosphere, as was done by Lord Kelvin, and (2) by seeking to explore the possible connections between the observed waves and the manometric waves due to temperature effects in the lower strata. The first of these theories must be abandoned for weighty reasons: (1) because the double wave does not exist throughout the atmosphere, as has been stated, but is confined to the lowest strata; (2) because the double wave system breaks at the latitudes 60° north and south, and reappears in the polar zones at right angles to that system,³ with a change in the phase of 90°; and (3) because there is no known physical principle requiring the existence

of any semidiurnal forced wave system. The second theory is not satisfactory because it has been found impossible to establish any positive synchronism in its details between the temperature changes and the corresponding diurnal variations of pressure due to manometric heat effects. Dr. Julius Hann for years sought to explain the phenomena along these lines, but was obliged to abandon the attempt and to accept Lord Kelvin's dynamic wave theory for want of anything better at hand.

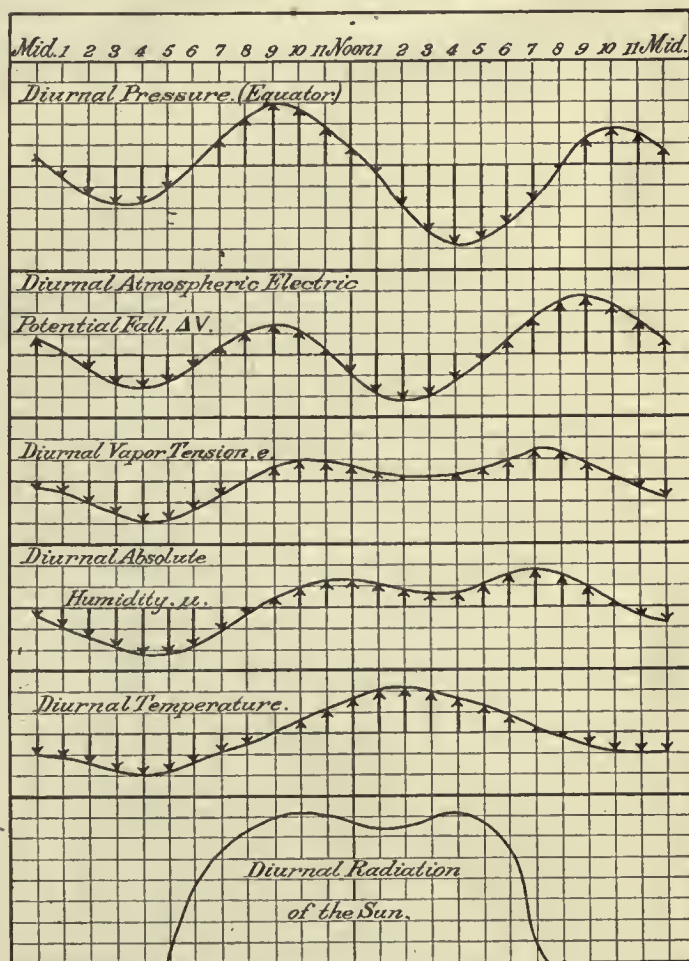


FIG. 1.—Diurnal variations of the meteorological elements in the atmosphere at the surface of the earth.

Like so many other scientific problems which are difficult of solution, the trouble apparently lies in the fact that the necessary observations have not been made in the right place. It was supposed that the variations noted at the ground were common to the adjacent strata up to considerable heights, but since meteorologists have succeeded in getting some upper

¹ Read before the Physics Section, B, of the American Association for the Advancement of Science at the Washington, D. C., meeting, December 28, 1902.

² Compare pages 120 and 121 of my paper, Eclipse Meteorology and Allied Problems, Weather Bureau Bulletin I, 1902.

³ International Cloud Report, chapter 9.

air observations, this supposition turns out to be contrary to fact, as is indicated by fig. 2.

Figure 2 is based on data that are now easily accessible, and we need not quote the authorities in detail. Generally speaking, when we go upward from the surface of the ground into the atmosphere, all the double diurnal periods become single periods, and this occurs at a comparatively low elevation. Thus at the top of the Eifel Tower the double periods greatly

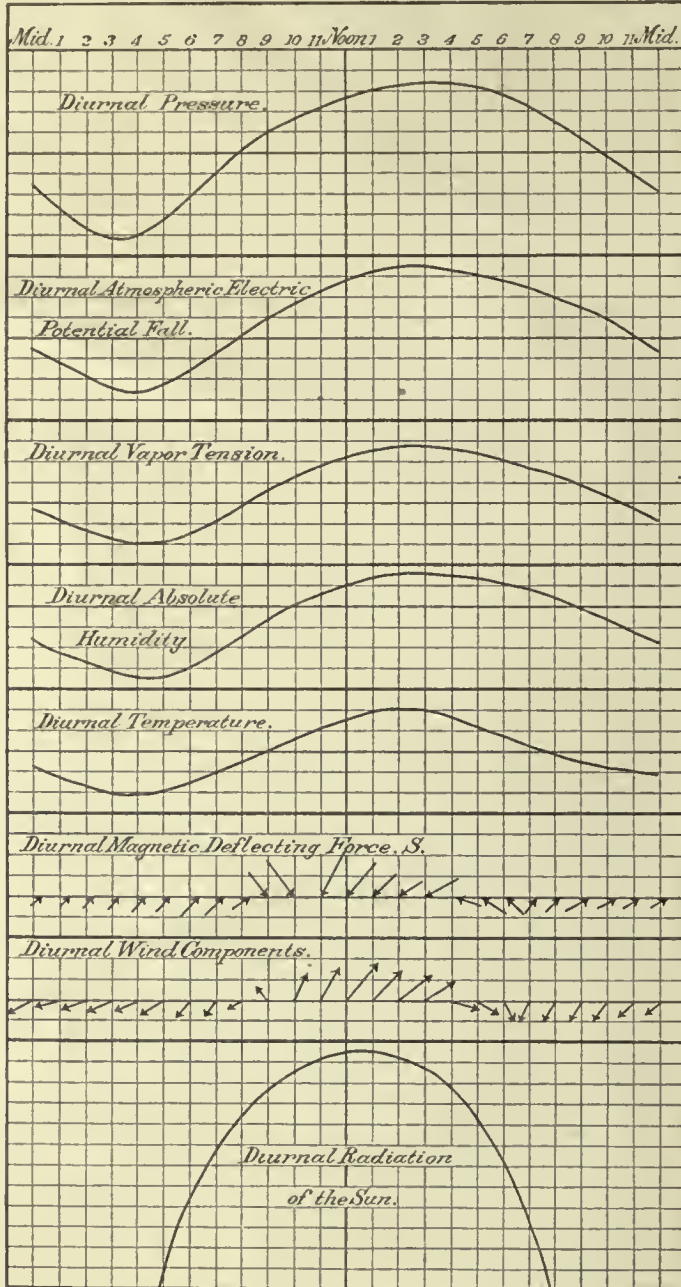


FIG. 2.—Diurnal variations of the meteorological, electrical, and magnetic elements in the atmosphere at some distance above the ground.

weaken or entirely disappear, and at the elevation of one or two miles, where the convectational ascents of the aqueous vapor contents of the air cease to form cumulus clouds, only the single period seems to exist. Thus the truncated actinometer curve with serrated top, fig. 1, becomes the parabolic curve, fig. 2, even at the surface when observed in very dry atmosphere; the barometric pressure curve and the vapor tension or the absolute humidity curves synchronize with the surface

temperature curve, which itself retains the single period as high up as any diurnal variations occur, and the electric potential fall becomes a single period curve at surprisingly short distances above the surface. Finally, in the temperate zones the diurnal wind components, and the magnetic deflecting vectors of the earth's magnetic field, not only agree together as vectors constituting a single system, but they also synchronize in their turning points and phases with all the other elements just mentioned. It is impracticable to go through a full description of the local exceptions to the general conditions, but they form a most interesting study for the meteorologist who keeps in mind their significance in connection with the great cosmical problems in physics. Enough has been said to show that we need to fix our attention upon the cause of the transformation of the double period into the single period in the lowest strata of the atmosphere.

The solar radiation.—In my judgment there can be but one line of argument that needs to be discussed, namely, the behavior of the aqueous vapor in the presence of the solar and the terrestrial radiations. The water content of the atmosphere at any elevation is determined by the temperature and humidity of the air, and therefore the unit volumes containing equal vapor contents stand upon isothermal surfaces which span the Tropics in great arches, stretching from the north polar zone to the south polar zone. These vapor contents rise daily from lower to higher levels during the forenoon and midday, but sink back again during the afternoon and evening hours. The process is well understood and it is briefly as follows: The incoming solar radiation of short waves penetrates the earth's atmosphere, with depletion of the short waves by selective reflection, and of the long waves by the absorption in the aqueous vapor; the earth's surface is heated by the residue of the radiation, and it then radiates like a black body at its own temperature, which being relatively low limits the outward radiation to much longer terrestrial waves than the incoming solar rays. The heat received at the surface also evaporates the water of the surface, heats the lower strata, and raises the isotherms by convection currents as well as by radiation, till at the average elevation of 1000 to 2000 meters the vapor tends to condense or actually forms the visible clouds. The outgoing radiation is also depleted by aqueous vapor absorption, and this with greatly increased vigor at the level where the water vapor turns into liquid water in the first stage of condensation. We have, therefore, a daily rise and fall of the vapor in the lower atmosphere, and it is the behavior of this vapor blanket which must be studied carefully to account for the transformation of the double daily into the single daily periods described above. But it will be desirable to examine a little more fully the peculiarities of the solar and the terrestrial radiations before going on to our conclusions.

Let J = the radiation from any single spectral line of a black body.

J_m = the maximum radiation occurring in the spectrum of a black body.

J_o = the total radiation throughout the whole spectrum from a unit surface of a black body.

λ = the wave length corresponding with J .

λ_m = the maximum wave length corresponding with J_m .

T_1 = the absolute temperature of the emitting body.

T_2 = the absolute temperature of the absorbing body.

A = the solar constant or the value of J_o at the distance of the earth from the sun.

R = the radius of the sun in kilometers.

d = the distance of the earth from the sun in kilometers.

Then we obtain by the Wien-Paschen formulæ in units of gram calories per cm^2 per second, per minute, and per day, respectively, the following equations:

Radiation function in the normal spectrum.

I. Radiation from a single spectral line in gram calories per cm^2 .

$$J = \frac{dJ_o}{d\lambda} = c_1 \lambda^{-5} 10^{-\frac{c_2 M}{\lambda T}}$$

$$= \frac{9.292 \times 10^3 \text{ Gr. Cal.}}{\lambda^5 \left(10^{\frac{6277.4}{\lambda T}}\right) \text{ cm}^2 \text{ second.}}$$

$$c_1 = \frac{1.277 \times 10^{-12} c_2^4}{6} = \frac{1.277 \times 10^{-12} (14455)^4}{6}$$

Logarithms.

$$= 9.292 \times 10^3 \text{ per sec.} \quad 0.96811$$

$$= 5.575 \times 10^5 \text{ per min.} \quad 5.74626$$

$$= 8.028 \times 10^5 \text{ per day.} \quad 8.90462$$

$$c_2 = 5 \times 2891 = 14455 \quad 4.16002$$

$$c^2 M = 14455 \times 0.43429 = 6277.4 \quad 3.79780$$

II. Total radiation of a black body.

$$J_o = 1.277 \times 10^{-12} (T_1^4 - T_2^4) \frac{\text{Gr. Cal.}}{\text{cm}^2} \text{ per sec.} \quad 8.10619-20$$

$$= 7.662 \times 10^{-11} (T_1^4 - T_2^4) \text{ " per min.} \quad 9.88434-20$$

$$= 1.1033 \times 10^{-7} (T_1^4 - T_2^4) \text{ " per day.} \quad 13.04270-20$$

$$\text{The solar constant } A = J_o \times \frac{R^2}{d^2}$$

$$= J_o \times 2.1643 \times 10^{-5} \text{ per min.} \quad 5.33532-10$$

$$\text{Radius of the sun. } R = 695\,500 \text{ kilometers.} \quad 5.84230$$

$$\text{Distance of earth from sun. } d = 149\,500\,000 \text{ kilos.} \quad 8.17464$$

$$A = 7.662 \times 10^{-11} (T_1^4 - T_2^4) \times 2.1643 \times 10^{-5}$$

$$= 1.6583 \times 10^{-15} (T_1^4 - T_2^4) \text{ per min.} \quad 5.21966-20$$

III. Maximum radiation in a normal spectrum.

$$J_m = \frac{c_1 5^5}{c_2^5 10^{5M}} T^5 = \frac{5.575 \times 10^5 \times 5^5}{(14455)^5 10^{2.17145}} T^5$$

$$= 3.1004 \times 10^{-16} T^5 \text{ per sec.} \quad 4.49141-20$$

$$= 1.8602 \times 10^{-14} T^5 \text{ per min.} \quad 6.26956-20$$

$$= 2.6787 \times 10^{-11} T^5 \text{ per day.} \quad 9.42792-20$$

$$\text{IV. } \frac{J_m}{J_o} = \frac{3.1004 \times 10^{-16} T^5}{1.277 \times 10^{-12} T^4} = 2.4289 \times 10^{-4} T \quad 6.38522-10$$

$$\text{V. } \lambda_m T = 2891. \quad 3.46105$$

(Eclipse Meteorology and Allied Problems, page 164.)

From formula IV we have the following equation:

$$J_m = 0.00024 T \times J_o.$$

Hence, for

$$T = 100^\circ; J_m = 0.024 J_o; \text{ and } J_o = 42 \quad J_m$$

$$T = 1000^\circ; J_m = 0.24 J_o; \quad J_o = 4.2 \quad J_m$$

$$T = 10000^\circ; J_m = 2.4 J_o; \quad J_o = 0.42 \quad J_m$$

That is to say for low temperatures the total radiation J_o is much greater than the maximum radiation J_m , but for high temperatures J_o becomes less than J_m . Since J_o is the integral of the area of the curve of energy intensity, it should evidently be greater than J_m under all circumstances, but the fact that by this formulæ (IV) it becomes less for temperatures above 4119° seems to indicate that there may be something wrong in the deduction of the formulæ III for J_m and II for J_o from which IV for $\frac{J_m}{J_o}$ was derived. These formulæ and constants

have been tested by numerous experiments, and they appear to be satisfactory for temperatures up to about $T = 1500^\circ$. It is noted that there is a tendency for the coefficients c_1, c_2 to change in passing from low temperatures and long wave lengths ($T = 273^\circ$ to 750°) to higher temperatures and longer wave lengths ($T = 750^\circ$ to 1500°). Compare page 164, Eclipse

Meteorology. At all these temperatures the ratio J_m/J_o seems to be normal, but at the higher solar temperatures this is no longer the case. It may therefore be the fact that the extrapolation to such temperatures as $T = 7000^\circ$ to 8000° is not allowable without a considerable change in these constants, or even in the exponents of the formula. It may be that there is a breakdown in the molecular structures of so-called black bodies at very high temperatures, which causes them to emit quite different spectra curves from those which we have computed by these formulæ. If this point of view is correct, it will be necessary to move very cautiously in computing the value of the solar constant, at the distance of the earth, from formulæ deduced in our laboratories and applied to the sun as to a common black body.

By means of these formulæ we construct the solar and terrestrial curves for various temperatures for the incoming radiation of the sun, supposing it to range from 8000° to 3000° ; also for the outgoing radiation from the earth with a range of from 383° to 198° absolute temperature. The corresponding coordinates are given in Tables 1 and 2; they are also plotted graphically on fig. 3 for the sun, and on fig. 4 for the earth. On the solar curve for $T = 6000^\circ$ is placed Professor Langley's energy curve as derived by the bolometer observations.

TABLE 1.—Energy spectra at solar temperatures reduced to the distance of the earth, expressed in units of gram calories per square centimeter per minute.

T.	8,000°	7,000°	6,000°	5,000°	4,000°	3,000°
$\lambda = 0.0\mu$	0.00					
0.1..	0.02	0.00	0.00			
0.2..	1.50	1.24	0.22	0.02		
0.3..	12.03	5.09	1.62	0.32	0.03	
0.4..	12.87	6.75	2.85	0.86	0.14	0.01
0.5..	10.41	6.21	3.12	1.19	0.28	0.03
0.6..	7.64	4.96	2.80	1.25	0.38	0.05
0.7..	5.43	3.76	2.30	1.15	0.40	0.07
0.8..	3.85	2.79	1.81	0.99	0.40	0.09
0.9..	2.81	2.06	1.41	0.82	0.37	0.10
1.0..	1.98	1.53	1.09	0.67	0.33	0.10
1.1..	1.45	1.15	0.84	0.54	0.28	0.09
1.2..	1.08	0.87	0.65	0.44	0.24	0.09
1.3..	0.81	0.66	0.51	0.34	0.20	0.08
1.4..	0.62	0.52	0.40	0.28	0.17	0.07
1.5..	0.48	0.40	0.32	0.23	0.14	0.06
1.6..	0.39	0.32	0.26	0.19	0.12	0.06
1.7..	0.30	0.25	0.21	0.16	0.10	0.05
1.8..	0.23	0.20	0.17	0.13	0.09	0.04
1.9..	0.19	0.16	0.14	0.11	0.07	0.04
2.0..	0.15	0.13	0.11	0.09	0.06	0.03
2.5..	0.06	0.05	0.05	0.04	0.03	0.02
3.0..	0.03	0.03	0.02	0.02	0.02	0.01
$J_m \dots$	13.19	6.77	3.13	1.26	0.41	0.10
$\lambda_m \dots$	0.36 μ	0.41 μ	0.48 μ	0.58 μ	0.72 μ	0.96 μ
A ...	6.79	3.98	2.15	1.04	0.43	0.13

$$J = \frac{5.575 \times 10^5}{\lambda^5 \left(10^{\frac{6277.4}{\lambda T}}\right)}$$

$$J \text{ in units } \frac{\text{Gr. Cal.}}{\text{cm}^2 \text{ minute.}}$$

TABLE 2.—Energy spectra at terrestrial temperatures, expressed in units of gram calories per square centimeter per minute.

T.	383°	373°	323°	303°	288°	273°	258°	243°	228°	213°	198°
$\lambda = 2\mu \dots$	0.000										
3...	.008	.006	.001								
4...	.044	.034	.007	.004	.002	.001					
6...	.134	.113	.041	.025	.017	.011	.006	.004	.002	.001	.000
8...	.152	.134	.063	.044	.032	.023	.015	.010	.006	.004	.002
10...	.128	.116	.064	.047	.037	.028	.021	.015	.010	.006	.004
12...	.097	.089	.055	.042	.034	.027	.021	.016	.012	.008	.005
14...	.070	.065	.042	.034	.028	.024	.019	.015	.011	.008	.006
16...	.050	.047	.032	.027	.023	.019	.016	.013	.010	.007	.006
18...	.036	.034	.025	.021	.018	.016	.013	.011	.009	.007	.005
20...	.027	.025	.019	.016	.014	.012	.011	.009	.007	.006	.005
22...	.019	.018	.014	.012	.011	.010	.009	.007	.006	.005	.004
24...	.015	.014	.011	.010	.009	.008	.007	.006	.005	.004	.003
26...	.011	.011	.008	.007	.007	.006	.005	.004	.003	.003	.002
28...	.008	.008	.007	.006	.005	.005	.004	.004	.003	.003	.002
30...	.007	.006	.005	.005	.004	.004	.004	.003	.003	.002	.002
32...	.006	.005	.004	.004	.004	.003	.003	.003	.003	.002	.002
34...	.004	.004	.003	.003	.003	.002	.002	.002	.002	.002	.001
36...	.003	.003	.003	.003	.003	.002	.002	.002	.002	.001	.001
38...	.003	.003	.002	.002	.002	.001	.001	.001	.001	.001	.001
40...	.002	.002	.002	.002	.002	.001	.001	.001	.001	.001	.001
$J_m \dots$	.153	.134	.065	.048	.037	.028	.021	.016	.011	.008	.006
$\lambda_m \dots$	7.55 μ	7.75 μ	8.95 μ	9.54 μ	10.0 μ	10.6 μ	11.2 μ	11.9 μ	12.7 μ	13.6 μ	14.6 μ
$J_o \dots$	1.649	1.483	0.834	0.646	0.527	0.426	0.340	0.267	0.207	0.158	0.118

Remarks on the solar constant.—This exhibit suggests some

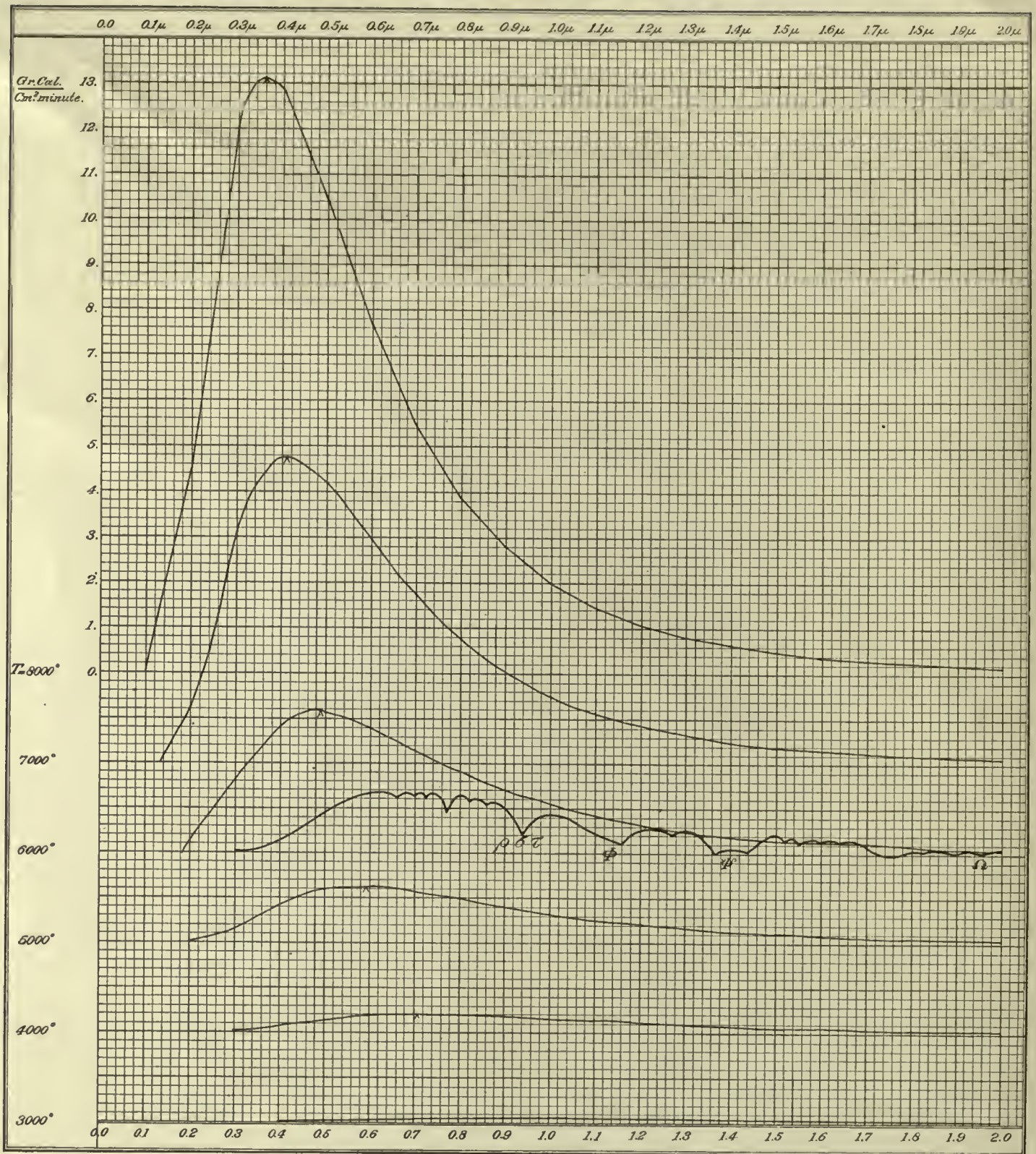


FIG. 3.—Energy spectra at solar temperatures reduced to the distance of the earth.

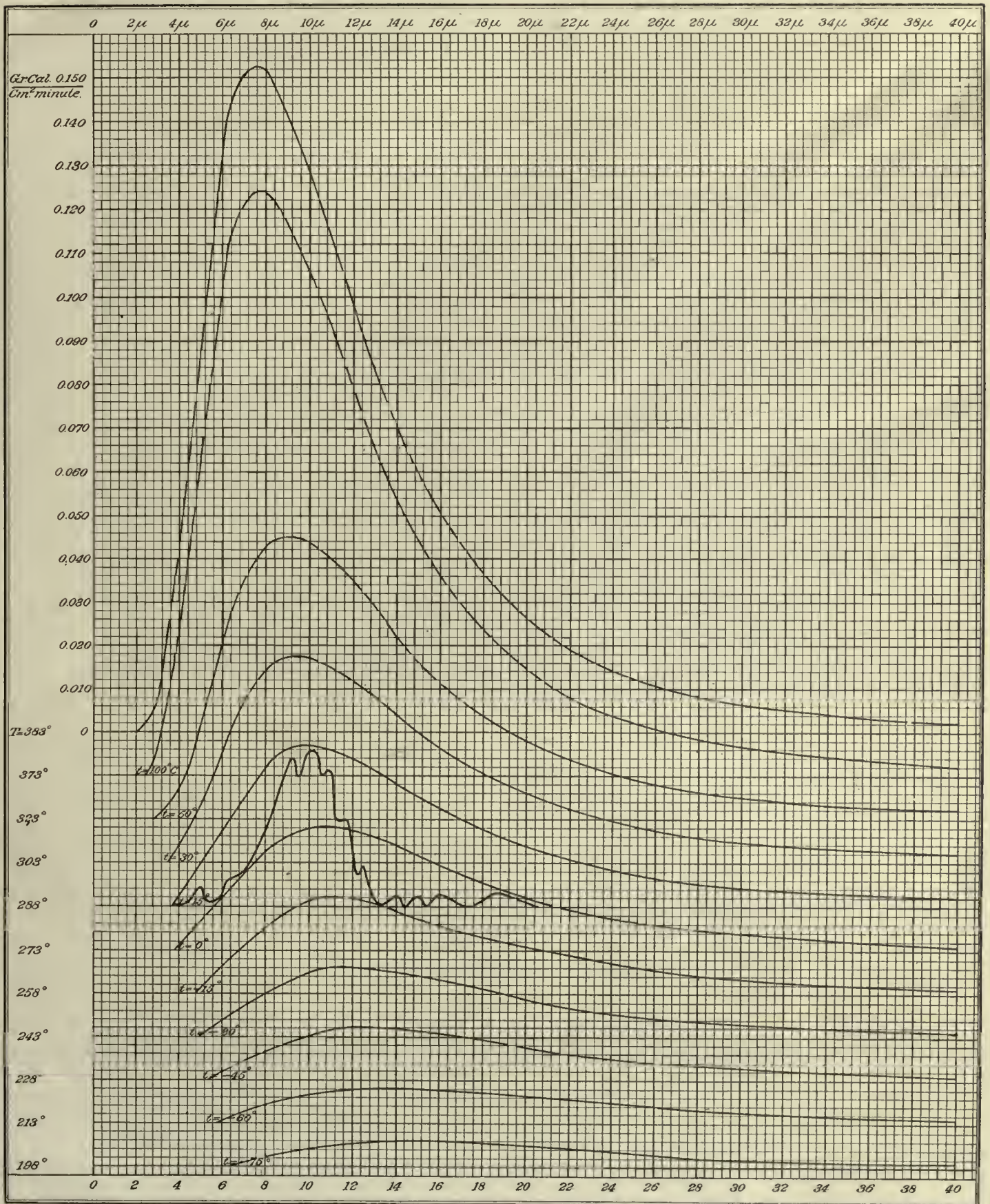


FIG. 4.—Energy spectra at terrestrial temperatures.

comments on the depletion of the short waves by selective reflection or scattering, and of the long waves through absorption by aqueous vapor. According to F. W. Very's discussions,⁴ the selective depletion and absorption in the solar atmosphere of the radiation from the photosphere, may be due to four cooperating causes: (1) to a considerable extension of finely divided solar material in the outer corona to the distance of about one radius; (2) to scattering upon the molecules and other very fine particles especially in the inner corona; (3) to the passage through a columnar structure having different coefficients of transmission; (4) to emission from the uneven granular surface of the photosphere radiating at different temperatures. According to Professor Schuster's recent paper,⁵ the depletion effect can be suitably explained by "placing the absorbing layer sufficiently near the photosphere and taking account of the radiation which this layer, owing to its high temperature, must itself emit." It is not proper to regard the radiating photosphere as of a single temperature, but as ranging somewhat, though not through many hundred degrees, with the depth of the strata, the lower being hotter; the coefficients of transmission vary with the wave length, and with the extent of path traversed, and therefore with the marginal distance of the ray from the center of the sun, the marginal transmission being rendered more efficient by early sifting out of the rays that are easily absorbed by the existing material. In the present stage of the problem it is difficult to assign the exact percentage of absorption due to the sun's atmosphere taken as a whole, and, from similar considerations, the percentage due to the absorption in the earth's atmosphere remains in doubt. Hence, it is not easy to derive the true temperature of the sun's radiating surface, even taken as an integral. Comparing the Langley curve with the energy curve for 6000°, it suggests that the short wave ordinates imply a temperature of about 5000°, but that the long waves at the same time require a temperature of rather more than 7000°, especially as indicated by those from 1.5 μ to 1.7 μ . Dr. Niles Ekholm⁶ attempts to reconcile these conflicting facts by assigning a system of varying temperatures, $T = 5226 + 1000\lambda$, increasing with the wave length, till T equals 7226° for $\lambda = 2.0\mu$. While this brings the two curves nearer together throughout their extent there are two difficulties yet to be overcome: (1) the sun's atmosphere depletes short waves most in its lower strata, while the long waves escape more readily, some of them apparently quite unaffected. Since the short waves by Ekholm's hypothesis are assigned to lower temperatures, this implies that they are emitted only by the higher strata in the sun's atmosphere, and therefore it follows that they do not register the temperature of the photosphere at all accurately. Furthermore, the temperature in the solar atmosphere above the photosphere can not have a range of 2000°. (2) If the long waves which actually pass through both the atmospheres of the sun and the earth do possess energy ordinates corresponding to temperatures as high as 7200° to 7500° they could not have been generated at all except at such high temperatures as these, and they in fact become an important index for determining the efficient photospheric temperature. It seems to me that since the long wave radiation at 1.5 μ to 1.7 μ requires a temperature of nearly 7500° we must let this fact control our conclusions, rather than depend upon the deductions to be derived from estimated percentage depletions of the short waves of the spectrum. It is noted that this gives a result nearly in harmony with the temperature $T = 7535^\circ$, which was assigned by me to the photo-

sphere from meteorological considerations (Eclipse Meteorology, page 81). Thus, in determining the hydrogen gas constant at the sun, we have,

$$R = \frac{p_0}{\rho_0 T_0} = \frac{10333 \text{ (earth)}}{0.089996 \times 273^\circ} = \frac{285185 \text{ (sun)}}{0.089996 \times 7535^\circ} = 420.55.$$

Since p (sun) = $10333 \times 27.6 = 285185$, it follows that $273^\circ \times 27.6 = 7535^\circ$, is the absolute temperature of the photosphere.

It was found that the rate of change of temperature from the photosphere vertically outward seems to be rather small, $\frac{dT}{dt} = -0.013^\circ$ per 1000 meters, that is, about 300° from the photosphere to the top of the inner corona, and this would indicate that we do not have in the sun's upper atmosphere such extremes of temperature to deal with as Ekholm's formula requires. But if we assign so high a temperature as 7535° to the photosphere, the depletion by scattering as shown by the diagrams of fig. 3 must be much greater than usually assigned, as is evident by comparing the curves, and we must also infer that the solar constant is really large in order to correspond to this temperature, namely, about 4.0 gram calories per square centimeter per minute at the outer limits of the earth's atmosphere.

In the earth's atmosphere selective scattering takes place on the molecules of the constituents of the air, especially in the lower strata, and absorption occurs throughout the shell occupied by the aqueous vapor, but also chiefly in the lower strata. It is again difficult to assign the relative parts due to scattering and absorption, respectively. Prof. F. W. Very contends that the aqueous vapor of the higher strata first attacks the incoming radiation and depletes it very considerably and thus raises the temperatures of the high strata. Our international cloud observations, and the direct temperature readings in balloon ascensions seem to sustain this view. But Ekholm argues from the heat content of the atmosphere, assuming the solar constant of 3.0 calories, as follows:

	Calories.
Solar constant = 3.0 calories per minute	3. 00
40 per cent absorbed = 0.40×3.0	1. 20
Inward.—(1). The air receives one-fourth of this	
and holds it	$\frac{432}{1440} = 0. 30$
(2). Conduction to be neglected	0. 00
(3). Convection to be neglected	0. 00
Outward.—(4). From vaporization of aqueous va-	
por	$\frac{164}{1440} = 0. 11$
(5). Radiation from earth = 50 per cent, where the surface receives $\frac{1}{3}$ of 3.00 = 1.00	$\frac{98}{1440} = 0. 07$
Total received per minute	$\frac{694}{1440} = 0. 48$

This corresponds to a mean temperature of the air 8.6°C. , while the observed mean temperature is -17.0°C. , or too low by 25.6°C. Ekholm says: "It follows that the supposed great absorption of heat by the atmosphere does not take place. But we must admit that the atmosphere absorbs directly only a small fraction of the insolation, and that it is chiefly warmed indirectly from the earth's surface." In a word, the aqueous bands absorb some little heat, while the air is nearly diathermanous to the rest of the energy spectrum. I shall, however, venture to raise the following inquiry. Ekholm seems to have assigned certain percentages for absorption, which of course are in the nature of a conjecture so long as the solar temperature remains in doubt, and a part of the discrepancy between the mean temperature of the earth's atmosphere as observed

⁴ Atmospheric Radiation, F. W. Very, Bulletin G, Weather Bureau, 1900. The solar constant, F. W. Very, Monthly Weather Review, August, 1901. The absorption power of the solar atmosphere, F. W. Very, Astrophysics, September, 1902.

⁵ The solar atmosphere, Arthur Schuster, Astrophysics, January, 1903.

⁶ Ueber Emission und Absorption der Wärme und deren Bedeutung für die Temperatur der Erdoberfläche, Meteorologische Zeitschrift, January, 1902.

and as deduced from the solar constant, may be explained in that way. But, furthermore, he seems to compute the total energy received on the basis of a twenty-four hour radiation, and to have made no allowance for the fact that the earth receives only twelve hours of sunshine. The solar constant per minute when applied to the residual temperature of the atmosphere should have this fact included, but I am not able to decide from Ekholm's paper whether this was done in fixing upon his percentages. I infer, in any event, that the common procedure of extrapolating to the value of the solar constant on the outer atmosphere by using the spectrum throughout its entire length assigns too much weight to the short waves, which certainly suffer severely from scattering, and that on the other hand the few long undepleted waves 1.5μ to 1.7μ which are neither absorbed nor scattered, form the proper basis for deducing the true solar constant. Judging from these data it is probably not far from 4.0 calories, and the temperature of the photosphere must be about 7500° .

The terrestrial radiation.—If the energy line plotted on curve T = 288° of fig. 4 represents the observed earth's transmission through the air as described by Very (see Bulletin G, page 124), it seems to be in conflict with the view that the earth radiates like a black body of low temperature. The strong absorption from $\lambda = 4\mu$ to 8μ is evidently due to aqueous vapor, but the much greater absorption area from $\lambda = 12\mu$ to 40μ is apparently not to be attributed to the same cause. It seems to me much more probable that the earth does not radiate these long waves like a black body, but is really deficient in them and emits freely only the waves from $\lambda = 4\mu$ to 12μ . On the other hand Ekholm⁷ has drawn the curve from 11μ to 20μ in quite a different manner, by extrapolating from Langley's corrected observations on the moon's radiation, so as to follow the normal energy curve much more closely.

Since no observations exist to determine this point it may still be left open to doubt whether the waves are emitted or not. If they are really emitted, then the air must have other absorbing constituents that have not yet been attributed to it to satisfy Very's curve.

We may now study briefly the effect of the earth's long-wave radiation upon the meteorological elements, and explain the occurrence of the double periods at the surface and single periods at the cumulus cloud levels. If the scattering effect throws back into space a considerable percentage of the incoming radiation so that it does not reach the earth at all, on the other hand the absorption by the aqueous vapor of the terrestrial long waves tends to efficiently conserve the earth's temperatures which are high relatively to that of the interplanetary space, and at the same time it generates a series of interesting physical processes which can be described with at least approximate correctness. A field of research of unusual importance and interest is here presented to the meteorologist. The discussion of the temperature and vapor pressure observations which have been taken in the United States during the past thirty years, is now going on at the Weather Bureau, and we hope to be able to make some further contributions to this subject by extending to the further study of the cloud formations those thermodynamic processes which were applied in a few cases in the International Cloud Report.

We adopt the hypothesis that aside from a moderate absorption of solar radiation by the aqueous vapor in the atmosphere, the waves pass through it unimpeded, except by scattering, which turns back a considerable percentage into space. The energy of the portion reaching the earth's surface is expended in raising its surface temperature. This increases from early morning till midday, with a lag of about two hours due to the slowness of propagation of the physical effects into

the atmosphere, and then declines in the reverse order till midnight. The earth radiates in the forenoon something like a black body of gradually increasing temperature, the longest waves being possibly excluded, though their energy has not yet been mapped out beyond $\lambda = 12\mu$. The aqueous vapor depletes the outgoing radiation strongly in the waves 4μ to 8μ and probably from 12μ to 20μ . It is especially to be noted that when water vapor turns to liquid water in cloud condensation the power of aqueous absorption is increased a hundred fold, and thus the generation of clouds forms at the same time an absorbing screen at the cumulus level which practically confines the radiation emanating from the land and the ocean to the strata within a mile or two above the earth's surface. Carbon dioxide, CO_2 , can absorb only its own peculiar rays, and as these constitute only a small portion of the spectrum their total effect is small compared with that of the aqueous vapor.

Explanation of the formation of the two types of diurnal periods.—Let us illustrate the formation of the double diurnal period at the earth's surface and the single period in the cumulus level by considering the behavior of the absolute humidity, that is the number of grams of water vapor per cubic centimeter. The first diurnal effect of the radiation from the earth is to raise the vapor content of the atmosphere from the low level occupied by it at night to a higher level during midday. This absorbing screen of water vapor, visible or not, rises and falls once daily through 1000 or 2000 meters, taken as a whole. While the warm air rises by convection from the surface to the level of 1500 meters, the vapor rises with it and endeavors to saturate the unit volumes of the higher strata at the prevailing lower temperatures, the depleted lower volumes being partially filled up again by fresh evaporation from the water and land surfaces. Thus, in fig. 5, which represents the humidity

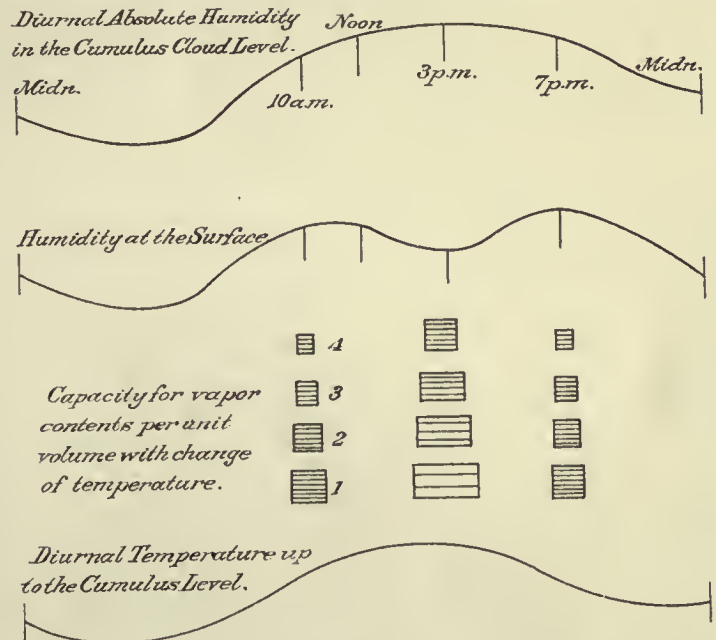


FIG. 5.—Illustrating the formation of the double and single diurnal periods of the absolute humidity.

variations at the earth's surface and at the cumulus level, and the temperature changes at all levels up to a moderate elevation of probably 3000 or 4000 meters, we may consider the behavior of the successive volume capacities arranged in vertical lines. There is a decrease in actual temperature with the elevation, and therefore the saturated unit-volume content decreases. The vapor sheet rises to higher levels, and this, together with the fresh supply by evaporation from the surface, can refill the depleted volume again, especially during

⁷ Ueber Emission und Absorption der Wärme und deren Bedeutung für die Temperatur der Erdoberfläche. Nils Ekholm, Met. Zeit., November, 1902.

the forenoon hours. After the noon hour the continued increase of temperature gives rise to larger vapor capacity per unit-volume, represented by larger areas on the diagram which are shaded more thinly and decrease upward in dimensions. But while the rising vapor sheet keeps the upper volumes filled, the lower, which are drained by the ascension of the water vapor, can not be supplied by evaporation at the surface at a sufficiently rapid rate to keep them full, because the prevailing surface moisture has been taken up at an earlier hour. The same remarks are true for the relative humidities. The result is that the upper volumes are always full, or relatively full, and have an increasing actual content up to the early afternoon, about 2 p. m., so that the diurnal curve at some distance above the ground has a single maximum and minimum as observed. On the other hand, while the 10 a. m. surface volumes are kept filled, or relatively filled, they are actually depleted in the afternoon and are not replenished by evaporation up to the original relative humidity of the morning, and therefore the curve shows a depression in the early afternoon, and is doubly periodic. The second maximum at the surface is due to a reversal of this process as the vapor settles back slowly to the ground during the afternoon and night. The additional lag of the evening maximum, being four hours in the evening to about 10 p. m., is due to the slow cooling of the ground after sunset, which continues to be a source of heat for several hours, and the slow conductivity of the heated atmosphere, which retains its heat even longer than the ground after the sun has set. This theory, if pursued into quantitative details will evidently account for the entire series of observed phenomena, and I hope to continue the study of this subject with such data as are now at the disposal of meteorologists. If we compare the areas of the complete actinometer curve of fig. 2 with that of fig. 1, as it is observed, the truncated portion must represent the heat energy that has been converted into work in carrying out these physical processes. Like an engine indicator-diagram, the difference between these curves can be translated as a function of the process concerned in the double diurnal periods in the lower strata, and thus become an important means of studying this function in the free atmosphere. If we could have suitable observations of the several elements at all levels up to 1 or 2 miles high, it would be a comparatively easy problem to discuss to a conclusion. At present the serious difficulty is to secure the necessary data since we must resort to more or less indirect methods.

The remaining elements may be treated for the change of period in a very few words. Analyzing the diurnal barometric pressure by volume contents we see that with the heating of the lower strata the denser air of night is replaced by contents of lower density after midday; taking into account the lag, the lower volumes are depleted and the upper are filled relatively, thus producing the two types of periods. This is entirely analogous to the barometric pressures of winter and summer wherein the summer pressures are lower at the surface of the earth, but greater at some such level as 1500 to 2000 meters, the summer pressure corresponding to that of the diurnal pressure in the afternoon. The later diurnal lag in the evening to 10 o'clock is a function of the cooling of the lower atmosphere by convection and radiation, and the settling back of the vapor sheet to the surface of the ground. The details of this phenomenon, as given in chapter 9 of the International Cloud Report, can all be shown to be in accord with this view, especially since the efficient vapor action caused by the lifting of the vapor sheet through radiation occurs outside the polar zones, and is greatest in the Tropics. It should be admitted that we do not yet understand the cause of the change of the phase of the diurnal barometric pressure which takes place in the polar zones. It is inferred from these considerations that since the double diurnal period is confined to a thin sheet near the sur-

face, and does not extend throughout the atmosphere, Lord Kelvin's theory of a dynamic forced wave is not available for explaining this phenomenon. Dr. Hann's difficulties regarding the synchronism of the temperature with the diurnal barometric pressure will also probably disappear, because the local behavior of the vapor sheet in dry and moist localities will impose strongly modifying conditions upon the efficient action of the surface temperatures in respect to the two types of periods.

The fact that water vapor is a very powerful absorbent of given waves, and that this occurs chiefly in the cumulus level and not at the ground, indicates that it is the cloud temperatures which must be studied for synchronism rather than those of the free air near the surface of the earth. It is evident that a large task in observations must be executed by meteorologists before the details of these processes can be satisfactorily worked out.

From what was written in my report on Eclipse Meteorology and Allied Problems regarding the ionization of the atmosphere and the formation of electric potential, it becomes evident that temperature changes occur when the molecular structure of the aqueous vapor of the atmosphere undergoes modification by breaking up, at least temporarily, into atoms and ions. Since the transition from water vapor to liquid, in cloudy condensation, marks a sensitive condition, and since it is just at this instant that the terrestrial (not solar) radiation is most absorbed, therefore all the conditions favor an excessive generation of ions and a change in the electric potential gradient. The fact that this element follows strictly the two type periods seen in the humidity and the barometric pressure makes it necessary that the absorption of energy and the ionization should be resultant functions occurring together in one general process. I believe that all the complex details observed regarding atmospheric electricity will be explained along these lines. Finally, in fig. 2, it is indicated that the diurnal deflecting wind components and the magnetic deflecting vectors of the earth's field are in close synchronism throughout the twenty-four hours, but by comparing them with the diurnal radiation of the sun and the temperature it is seen that they are simply parts of the single period system which is common to all strata of the atmosphere, except the lowest, in the three elements described, namely, the barometric pressure, vapor tension, and electric potential gradients. We infer, then, that since the double period depends strictly on the convective rise and fall of the vapor sheet, the magnetic field is primarily more closely connected with the effects of the solar direct radiation throughout the atmosphere. What we lack in this connection is a series of observations to determine the variation of the magnetic components in the higher strata, which I doubt not will be found to be similar to those at the surface. In all respects it is evident that observation in the lower cloud region is as much demanded by the meteorologist as by the magnetician, to determine the subtle cross connections between the gaseous contents of the atmosphere and the electrical and the magnetical variations. But it seems to me very probable that the magnetic diurnal variations are due to a set of physical processes induced by the terrestrial radiation in the lower atmosphere. This may explain the fact that the incoming solar radiation does not seem to be the cause of the ionization which apparently precedes the generation of the electric and the magnetic disturbing forces. If this problem can be solved in the free air, it will probably also contribute important facts regarding our general knowledge of the relations between matter and ether. It is especially desirable to note that the facts which are now known indicate that the diurnal variation of the magnetic field of the earth is strictly a meteorological effect in the atmosphere, caused by the solar-terrestrial radiation, and that the order of production is (1) temperature, (2) electric potential, (3) magnetic deflection, somewhat as explained in Bulletin I, Eclipse Meteorology and Allied Problems.

II.—SYNCHRONOUS CHANGES IN THE SOLAR AND TERRESTRIAL ATMOSPHERES.

Read before Section A, Astronomy and Astrophysics, American Association for the Advancement of Science. Washington, D. C., December 28, 1902.

GENERAL REMARKS.

In my paper, "A contribution to cosmical meteorology," published in the MONTHLY WEATHER REVIEW for July, 1902, evidence was given of the fact that the variation in the solar output, as registered in the relative frequency of the sun spots, has a marked synchronism with the variation of the areas enclosed by the curves representing the horizontal magnetic force of the terrestrial field. This is of course well known from many investigations, but the special features of the paper showed that the sun spots constitute only a sluggish register of the solar activity, and that the terrestrial magnetic force exhibits a set of characteristic minor fluctuations superposed upon the general 11-year curve. These special variations reappear with marked distinctness in the solar prominences as measured by their observed frequency, and also in the variations of the mean annual barometric pressures in all portions of the earth. The significance of this exhibit is its indication that the pressures in the earth's atmosphere are undergoing changes in short cycles of about three years average duration, which correspond with the changes in the external work of the sun. A further study of our meteorological records during the past few months convinces me that these short cycles are produced by modifications in the general circulation of the earth's atmosphere, which produce alternate accelerations or retardations of general movements, and that these raise or lower the average annual barometric pressure over large districts of the earth's surface. There is also a sort of surging of the atmosphere with more or less stationary configurations or structures, and these involve the so-called seasonal climatic changes of weather by which one year differs from another. Thus, the regions about the Indian Ocean and South America vary synchronously but inversely; the continental and the ocean areas appear to change in an inverse manner; there seems to be a tendency to generate a great cyclic change having a period of about eight years within which the pressure excesses begin, for example in India, pass through Asia, Europe, North America, and South America back to India. This synchronism between the solar and terrestrial variations is found in the United States to hold for the pressures, temperatures, the storm-track movements in latitude and longitude, the cold-wave tracks, and generally for all the elements of the atmosphere. I have elsewhere sufficiently described my views regarding the causes of this synchronism, and it must be evident to all that meteorology has a great interest in elucidating these fundamental problems of solar physics, since our hope of making seasonal forecasts of the weather will be fulfilled only by reducing our knowledge of the complex connections between the sun and the earth to a scientific basis. I can at this time present the result of only one portion of my work in this direction, with an indication of the nature of the problems that must be solved by astrophysicists in order to perfect our knowledge of terrestrial meteorology.

DISTRIBUTION IN LONGITUDE.

It is desirable to study the distribution of the effects of the solar activity at the surface of the sun in both longitude and latitude, and their variations in the 11-year period. Passing

over the subject of the true period of the sun's rotation, which is now being discussed by scientists, and which would require a longer statement than is here possible, it may be noted that whatever period is adopted for an ephemeris, the frequency numbers for spots, faculae, and prominences collected in tables will show a drift to the right or left according as the period is too short or too long. For example, if in constructing an ephemeris one adopts as the mean period of rotation that which is proper to the sun spots at latitude $\varphi = 12^\circ$, which is 25.23 (sidereal) days with the diurnal angle 14.27° , as Spörer and Wolfer have done, and collects together the faculae in longitude, it is found that charts of successive rotations of the sun on this ephemeris show a trend to the right for the years 1887–1889, but a trend to the left in the years 1890–1892. This is due to the fact that just preceding the minimum of the solar-spot and faculae period, these formations occur chiefly in low latitudes, within 5° to 10° of the solar equator, but after the minimum in latitudes 20° to 25° . In the former set the rotational period is much shorter than in the latter, that preceding minimum being shorter, and that following minimum being longer, than the period at 12° latitude. Thus Wolfer finds the diurnal angle of rotation 14.41° (or rotational period 24.98 days) in latitude 5° , but 13.92° (with period 25.86 days) in latitude 22° , as against 14.27° (with period 25.23 days) in latitude 12° .¹

Wolfer's charts show a distinct trend to the right for the spots, faculae, and prominences during the years 1887–1889, but to the left for the years 1890–1892. In the case of the

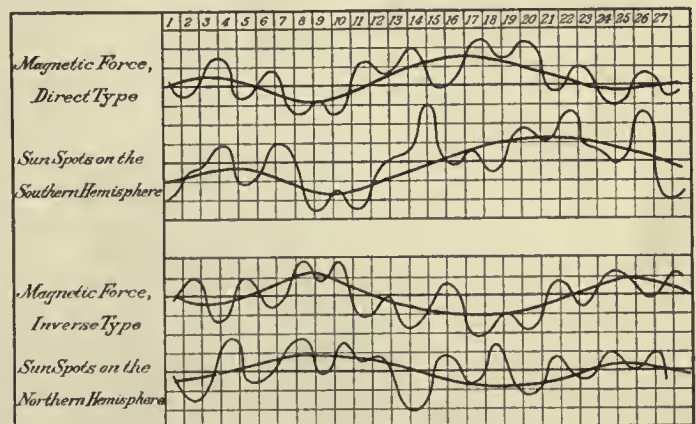


FIG. 1.—Comparison of the total sun-spot areas, 1854–1891, with the magnetic curves in the 26.68-day period.

prominences, which occur in all latitudes of the sun, we may expect to have an opportunity to discuss the surface rotation in higher latitudes than those of the spots and faculae, since these are confined to the zones $\pm 30^\circ$. I am engaged in such compilation of the data of the prominences observed in Italy from 1871 to 1900, but am not able to make any further statement at present. It is evident that whatever fundamental rotation period may be selected it can be corrected by the tabular drift as just indicated. There is to be noted, how-

¹ Publikationen der Sternwarte des Eidg. Polytechnikums zu Zurich. A. Wolfer. Bd. I, II, III. 1897, 1899, 1902. 9

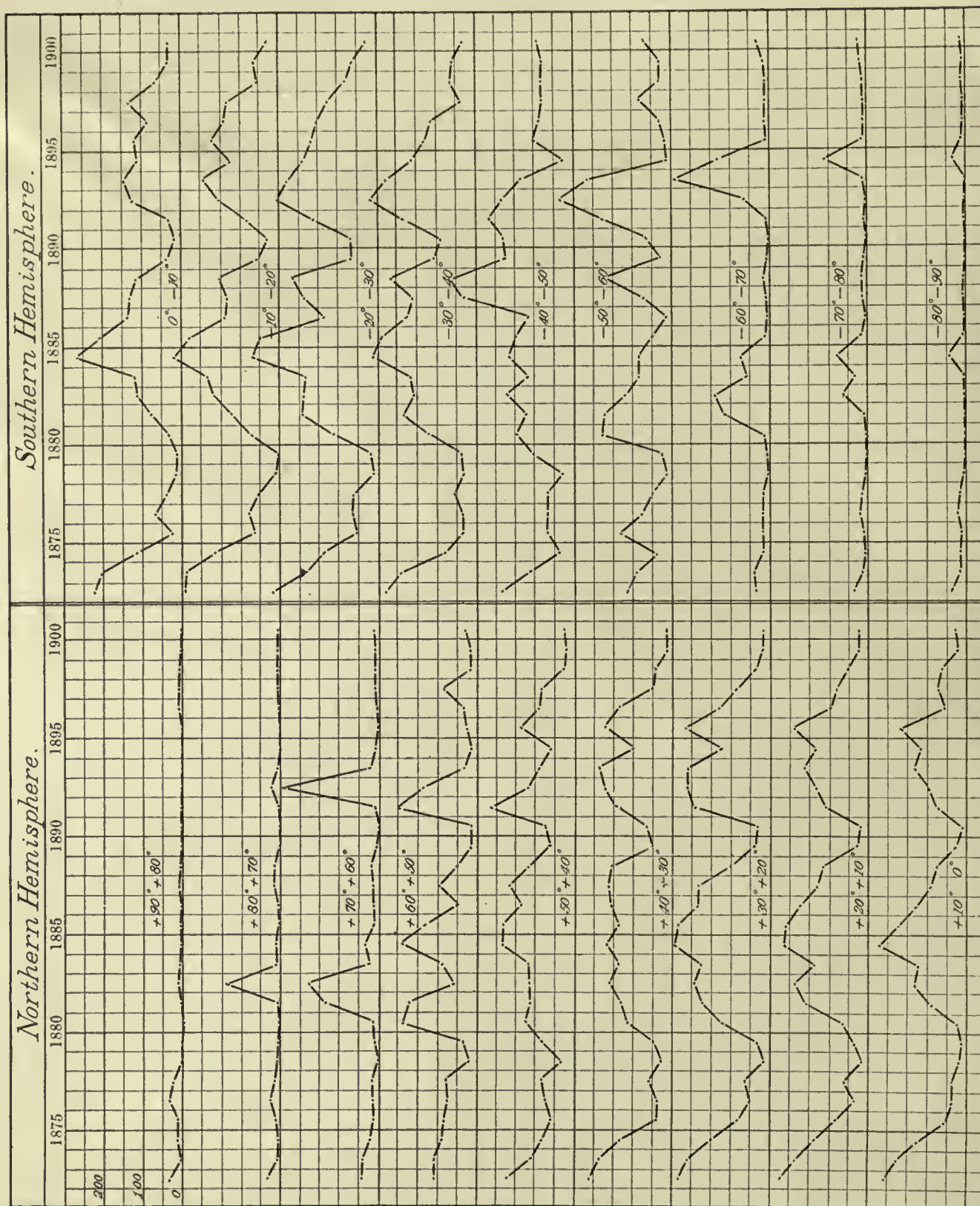


FIG. 2.—Observed variation of the relative frequency of the solar prominences in 10-degree zones.

ever, an important feature of the distribution in longitude as given on Wolfer's charts, namely, that the recurrence of the spots and faculae does not happen at random in all degrees of longitude, that is on all solar meridians, but they are arranged in two well defined group systems, which repeat themselves during many rotations, and these are located approximately on the extremities of a single diameter, that is, they occur on meridians about 180° apart. There seems to be a solar meridian plane on which the output is constitutionally more vigorous, or as Wolfer indicates the fact, the sun has centers of activity on opposite sides of its mass. This peculiar distribution along the equatorial belt would seem to imply that the mass of the sun tends to erupt more freely on opposite sides of the center along one of its diameters, and this may lead to some knowledge or inference as to its physical interior condition. It may be a viscous mass somewhat elliptical in shape, or at least affording freer egress for the escaping products of compression along one axis. This phenomenon is best seen at times of minimum activity, because near the maximum the output so far increases in vigor as to be distributed more equally in all longitudes, and to conceal this special tendency to concentrate along a given axis.

An entirely similar result was obtained in my discussion of the solar spots by taking an ephemeris based upon the period of the rotation at the equator, that is, 26.68 days (synodic). Compare Bulletin No. 21, Solar and Terrestrial Magnetism, Weather Bureau, 1898, page 141, or Bulletin I, Eclipse Meteorology, page, 91. The compilation of the deflecting vectors of the terrestrial magnetic force gives a curve of the same type as do the primary and secondary variations.

An inspection of the groups of spot numbers in the tables in which the data were collected does not indicate any tendency to drift to the right or left as one passes through the great 11-year cycles, and this shows that the spots have sufficiently short lives relatively to this period to be subordinate to the primary source of the output from the solar nucleus, which latter must have some properties independent of the observed surface phenomena themselves. The angular velocity of surface drift varies in latitude, but the internal action that produces spots appears to be united closely with the observed period at the equator itself, and there is also reason to believe that the period at the equator is the same as that at the poles. The equatorial plane may be assumed to rotate with the same velocity as the interior mass and to have the true period of rotation. The observations indicate that there is a structure which produces an excess of output on certain meridians about 180° apart. This is the result of our discussion of the distribution of the solar activity in longitude, and we will now proceed to consider the evidence that there is a structural distribution of energy in latitude.

DISTRIBUTION IN LATITUDE.

The Italian observations of the solar prominences made by Secchi, Tacchini, and Ricco, from the year 1871 up to the present time, published in the *Memorie della Società degli Spettroscopisti Italiani*, constitute a valuable series of data as homogeneous in character as it is possible to produce. A shorter series by Rev. J. Fenji, S. J., at the Haynald Observatory, Kalocsa, has been published for the years 1884 to 1890, inclusive, and additional volumes of this important work are in preparation. Sir Norman Lockyer has recently published in volume 70 of the *Proceedings of the Royal Society* some conclusions derived from the Italian data, but I have for myself collected together the frequency numbers for the sake of their bearing upon the problem of the circulation of the mass of the sun which is about to be described. Lockyer's curve and my own agree in showing the same variation of the annual frequency numbers for the years 1871 to 1900, inclusive. My compilation has been extended to include the solar spots and

faculae for the interval 1880 to 1900. For the years 1872-1877, Secchi collected his data by periods of solar rotation, using the period 27.78 days; for the years 1878-1900 Tacchini and Ricco have collected the data by the calendar months. I have reduced the Secchi series to the year intervals, in order to make the annual numbers homogeneous with the Tacchini series. The number of observations of the prominences, spots, and faculae has been distributed into 10-degree zones in latitude from the north pole to the south pole of the sun for each rotation and month, respectively, of the two series, that is, 90° to 80° , 80° to 70° , 70° to -80° , -80° to -90° . The sums are taken by zones, and also by rotations or months, and are checked by producing the same annual sum. The annual numbers of prominences, spots, and faculae, respectively, were plotted on diagrams in order to exhibit the changes going on in the sun during the three past 11-year cycles, but these charts and the expanded tables are not reproduced in this present paper.

It was concluded, as the result of a careful examination of the charts, that the average variation of the output could be most satisfactorily reduced to a law by combining these three cycles together, and thus eliminating to some extent two sources of irregularity, (1) that due to the spasmodic action of the sun, and (2) that caused by the difference of cloudiness from season to season in Italy, which modified the number of days available for the observations. The numbers are collected in groups of three years each, beginning 1872, 1883, 1894, as shown in Tables 1 and 2. The years which correspond with each other in the 11-year cycle are placed together, and it makes no difference where the mean cycle begins to be numbered. By passing down the table from 1872, three times in succession, the annual numbers are found, and can be used in other discussions. The data are now exhibited in several ways. On fig. 2 is given the variations found by plotting the annual numbers in each 10-degree zone in succession for the years 1872-1901. Thus, in the 90° to 80° zone of the northern hemisphere we have from Table 1 the numbers 35, 3, 9, 10, which give the first broken line of the chart. Viewing this chart as a whole we make the following notes: (1) The 11-year cycle variation is strongly developed in the equatorial zones and diminishes in intensity toward the polar zones, where it has nearly disappeared. (2) By plotting the mean annual numbers only the prominence variation line is produced; see the first curve of fig. 28, in my article No. VII, "A contribution to cosmical meteorology," published in the *MONTHLY WEATHER REVIEW* for July, 1902. (3) Although there is considerable variation in the amplitude of the same annual frequency number, that is, in the series of crests formed during the same year in different zones, it is evident that the sun is affected throughout its photosphere by the increase and decrease of the output of energy as registered in the prominence numbers. (4) The irregularity, however, is so large as to show that the sun acts like a congested and discharging viscous mass, through a series of distortions, accelerations, and retardations, in different parts of its mass, and that it does not transfer its internal energy into outside work uniformly and symmetrically. It is extremely important to remember this because in discussing the data for the period of the solar rotation, *we do not have a series of independent events to combine*, as the theory of least squares or the law of errors demands. It is preferable to work out the period by methods more practical than the application of the Fourier series and the Schuster periodogram, which depend upon the occurrence of independent events, and an expectancy based upon the law of errors. The sun does not exhibit a steady potential system of either electric or magnetic forces, nor any steady recurrence of events upon its surface which can be combined by rigid analytic laws. This is a natural consequence of the fact that the mass of the sun fills an immense volume in space and is experiencing congestion and escape of

TABLE 1.—Mean observed distribution in latitude during the 11-year solar cycle. Solar prominences.

Years.	90° 80	80° 70	70° 60	60° 50	50° 40	40° 30	30° 20	20° 10	10° 0	0° -10	-10° -20	-20° -30	-30° -40	-40° -50	-50° -60	-60° -70	-70° -80	-80° -90	Annual sums.
(1)																			
1872.....	35	39	47	106	164	218	229	225	207	216	246	270	234	184	120	33	34	38	2,645
1883.....	9	10	22	97	116	141	172	138	125	121	187	193	169	112	88	56	32	8	1,796
1894.....	2	1	9	15	58	99	125	136	116	111	123	196	161	30	14	130	106	35	1,467
Mean.....	15	17	26	73	113	153	175	166	149	149	185	220	188	109	74	73	57	27	1,969
(2)																			
1873.....	3	10	38	107	107	181	206	165	175	201	235	182	188	106	92	40	7	10	2,053
1884.....	3	11	42	195	191	165	245	213	217	263	266	322	265	164	91	72	83	48	2,856
1895.....	0	1	4	29	131	169	212	194	166	124	171	167	135	101	20	3	7	6	1,640
Mean.....	2	7	28	110	143	172	221	191	186	196	224	224	196	124	68	38	32	21	2,183
(3)																			
1874.....	9	5	24	94	84	130	150	141	125	116	161	138	82	93	44	10	2	7	1,415
1885.....	3	3	17	139	181	139	229	208	175	201	232	299	242	148	48	6	12	2	2,284
1896.....	6	3	4	37	93	141	131	100	53	89	147	151	117	92	28	9	7	3	1,211
Mean.....	6	4	15	90	119	137	170	150	118	135	180	196	147	111	40	8	7	4	1,637
(4)																			
1875.....	10	13	15	87	60	46	78	81	55	26	61	52	44	61	137	19	5	6	856
1886.....	1	9	18	48	132	152	180	172	130	141	146	139	174	116	16	4	5	2	1,585
1897.....	4	6	8	90	81	52	91	85	74	138	139	126	41	76	80	11	6	5	1,113
Mean.....	5	9	10	75	91	83	116	113	86	102	115	106	86	84	78	11	5	4	1,185
(5)																			
1876.....	40	29	19	76	75	39	50	43	41	66	84	65	44	66	77	19	20	23	876
1887.....	12	15	15	99	102	161	178	136	96	134	140	192	156	287	70	9	12	3	1,877
1898.....	5	9	12	17	26	47	39	52	59	62	102	89	61	79	29	13	11	9	721
Mean.....	19	18	15	64	88	82	89	77	65	87	109	115	87	144	59	14	14	12	1,158
(6)																			
1877.....	25	18	17	33	78	53	62	57	39	43	52	60	54	64	50	13	13	11	742
1888.....	8	16	25	49	117	152	99	116	75	110	155	216	220	317	176	16	15	5	1,887
1899.....	5	10	11	16	23	13	17	24	24	31	56	57	54	82	31	17	21	6	498
Mean.....	13	15	18	33	73	73	59	66	46	61	88	111	109	154	86	15	16	7	1,042
(7)																			
1878.....	1	7	3	19	34	34	13	16	17	12	9	8	35	31	8	1	3	1	252
1889.....	2	2	6	21	62	51	36	32	30	38	52	65	104	174	39	6	4	0	724
1900.....	5	9	16	36	30	18	19	25	27	35	31	32	31	96	68	31	24	10	543
Mean.....	3	6	8	25	42	34	23	24	25	28	31	35	57	100	38	13	10	4	506
(8)																			
1879.....	1	5	13	46	85	49	33	29	10	9	4	24	45	101	27	5	3	1	490
1890.....	3	1	0	19	75	66	29	22	11	15	30	69	96	185	61	1	0	2	685
Mean.....	2	3	7	33	80	58	31	26	11	12	17	47	71	143	44	3	2	2	588
(9)																			
1880.....	0	4	21	187	128	110	121	63	26	37	70	110	119	148	177	14	2	1	1,338
1891.....	3	5	16	199	215	146	182	107	69	31	91	160	183	220	178	17	7	4	1,836
Mean.....	2	5	19	193	172	128	152	85	48	36	81	135	151	184	178	16	5	3	1,587
(10)																			
1881.....	5	13	143	169	107	132	175	153	93	76	126	197	191	116	170	115	15	2	1,998
1892.....	0	23	247	137	119	172	207	136	98	124	154	252	272	183	283	62	2	1	2,472
Mean.....	3	18	195	153	113	152	191	145	96	100	140	225	232	150	227	89	9	2	2,235
(11)																			
1882.....	21	146	177	56	108	160	196	193	133	114	168	198	157	172	118	141	63	6	2,327
1893.....	0	10	25	29	93	187	206	158	132	149	195	229	226	138	208	242	13	1	2,241
Mean.....	11	128	101	43	101	174	201	176	133	132	182	214	192	155	163	192	38	4	2,284

heat energy generated by gravitational compression. It is, furthermore, necessary to free the solar data from terrestrial meteorological effects before any type of least square analysis can be properly applied. To emphasize this point more fully, Tables 3, 4, and 5, derived from the original tabulation, give the sums for each rotation or month, respectively, for the entire solar surface, by summing up the numbers found in the several zones. It is seen that in the monthly means of the prominences there is a very distinct annual variation in the number of prominences observed. This can be due only to the annual change in the Italian climatic conditions which affected the making of the observations, and it shows that the recorded frequency numbers are not free from a strong terrestrial term which must modify all discussions in solar physics, unless

satisfactorily eliminated. The tables for the solar faculae show the same seasonal variation as the prominences, but less conspicuously developed, while the sun-spot means are practically unaffected by the climatic changes. This difference must be attributed to the relative length or duration of the three phenomena, the spots having a life sufficiently long to bridge over the gaps covered by cloudy weather in Italy, so that the true number of spots which occur on the sun is really counted. This is true of the faculae to a lesser degree because their lives are shorter than the sun spots, and some come and go in the intervals of stormy weather without being enumerated at all. The prominence numbers especially are subject to loss by not being observed continuously, because their life is usually very brief, so that the prominences which occur in successive meridian areas

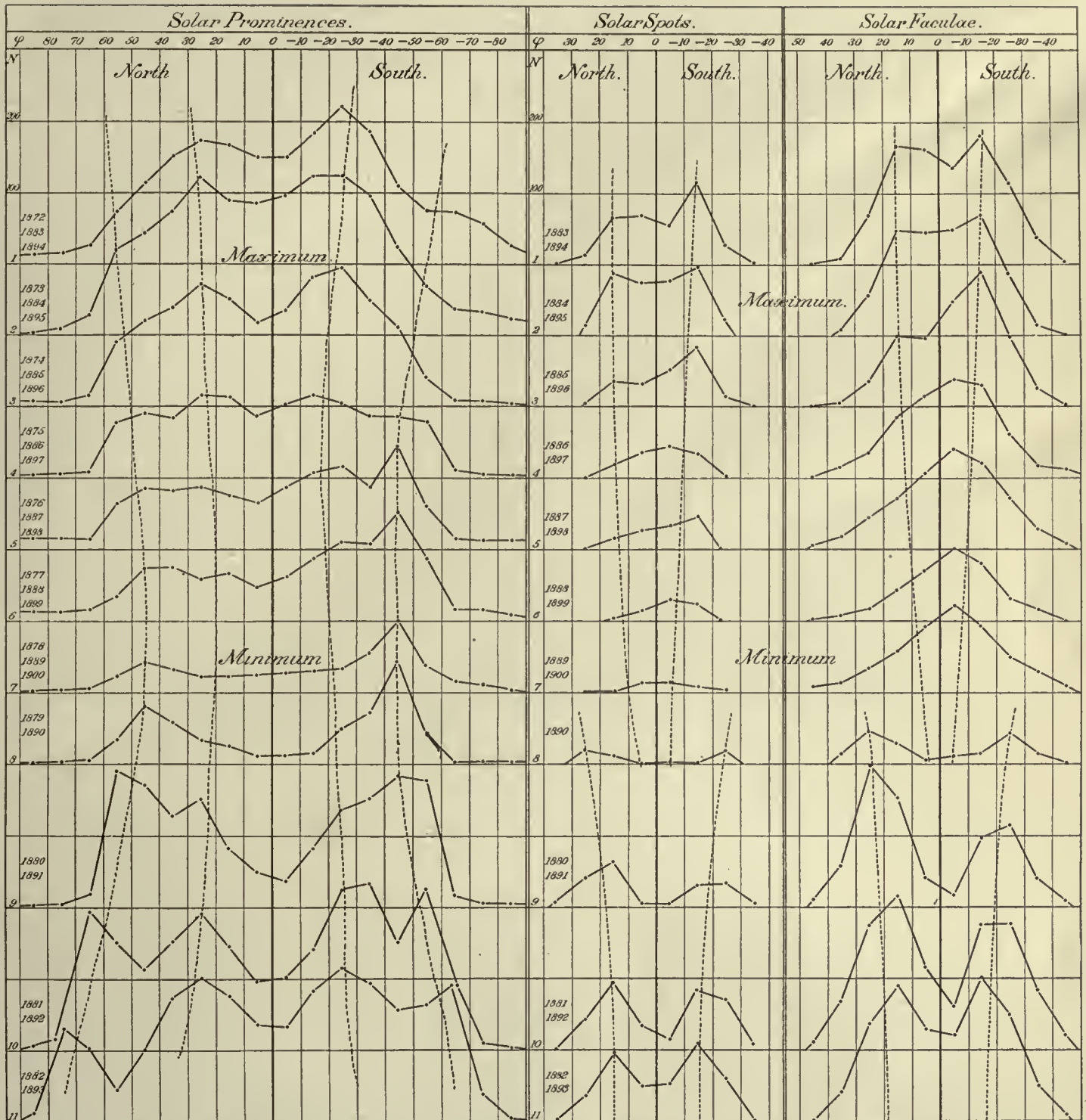


FIG. 3.—Mean variation of the distribution in latitude during the 11-year periods of the interval 1872-1900.

and are seen only on the edge of the sun can not be fully counted under ordinary observing conditions. The Kaloesa observations exhibit similar disturbances due to the conditions. If the observations of 1884-1890 be collected in a similar manner to that adopted above, we find that the numbers increase decidedly from 1884, which is a maximum year, to 1890 which is a minimum year, and this is contrary to the probable course of the events. The Italian observations decrease from 1884 to 1890, and the two series are opposite to each other in this respect, though they give similar zonal distributions so far as the maxima are concerned. Steadiness in observing and elimi-

nation of cloudy weather was therefore indispensable in order to procure reliable data for these discussions in solar physics. So far from being independent almost all solar data are mutually dependent upon adjacent events, and Professor Seluster's method of the periodogram is subject to this sort of limitation. The same is true of almost all the terrestrial meteorological elements, and generally a negative result which is derived from the discussion of a periodic or cyclic curve is valuable only when it is certain that the data conform to the analytic presuppositions, such as are laid down in the theory of the energy curve. Seluster applied his theory to the Green-

TABLE 2.—Mean observed distribution in latitude during the 11-year solar cycle. Solar spots and faculae.

Years.	SOLAR SPOTS.									SOLAR FACULÆ.										
	40° 30	30° 20	20° 10	10° 0	0° -10	-10° -20	-20° -30	-30° -40	Annual sums.	Above 40°	40° 30	30° 20	20° 10	10° 0	0° 10	-10° -20	-20° -30	-30° -40	Below -40°	Annual sums.
(1)																				
1883	1	7	57	63	58	107	20	.....	313	.....	7	68	175	154	117	159	89	24	.....	793
1894	1	21	71	73	56	129	33	3	387	1	6	64	152	166	154	199	139	53	7	941
Mean .	1	14	64	68	57	118	27	2	350	1	7	66	164	160	136	179	114	39	4	867
(2)																				
1884		11	92	85	109	113	22	.....	432	.....	4	44	135	143	174	168	69	11	.....	748
1895		19	85	61	44	82	24	.....	315	.....	9	69	161	145	121	167	104	14	1	791
Mean .		15	89	73	77	98	23	.....	374	.....	7	57	148	144	148	168	87	13	1	770
(3)																				
1885		3	32	38	75	80	6	2	236	1	2	20	97	99	164	169	40	2	.....	594
1896		2	41	28	29	89	19	.....	208	.....	7	55	100	96	129	209	156	45	5	802
Mean .		3	37	33	52	85	13	1	222	1	5	38	99	98	147	189	98	24	3	698
(4)																				
1886		1	21	17	32	25	2	.....	98	.....	4	8	39	47	70	63	23	3	1	258
1897			17	52	58	42	2	.....	171	3	25	62	129	181	207	197	96	27	19	946
Mean .		1	19	35	45	34	2	.....	135	2	15	35	84	114	139	130	60	15	10	602
(5)																				
1887		1	10	10	30	20	.....	.....	71	1	5	9	21	32	53	39	7	1	1	169
1898			23	45	38	74	.....	.....	180	6	32	76	122	181	226	200	133	53	15	1,044
Mean .		1	17	28	34	47	.....	.....	126	4	19	43	72	107	140	120	70	27	8	607
(6)																				
1888			3	14	35	10	.....	.....	62	.....	1	2	9	37	71	38	2	.....	.....	160
1899			6	15	25	40	.....	.....	86	8	15	36	75	103	130	118	62	33	2	582
Mean .			5	15	30	25	.....	.....	74	4	8	19	42	70	101	78	32	17	1	371
(7)																				
1889		3	0	5	15	3	8	.....	34	1	2	6	6	15	30	19	12	2	1	94
1900			4	21	18	14	.....	.....	57	15	28	65	112	171	211	168	90	57	20	937
Mean .		2	2	13	17	9	4	.....	46	8	15	36	59	93	121	94	51	30	11	516
(8)																				
1890		20	13	1	3	3	21	.....	61	.....	15	45	31	6	11	16	44	14	1	183
(9)																				
1880	6	24	45	8	7	33	32	3	158	19	85	244	150	45	21	124	146	60	14	908
1891		57	85	6	1	27	33	6	215	1	33	152	155	37	12	71	83	19	1	554
Mean .	6	41	65	7	4	30	33	5	187	10	59	198	153	41	17	98	115	40	8	731
(10)																				
1881		52	93	22	12	79	61	.....	319	15	109	253	279	121	58	195	187	92	32	1,341
1892	2	34	93	44	16	89	78	12	368	4	27	100	156	112	61	152	167	72	11	862
Mean .	1	43	93	33	14	84	70	6	344	10	68	177	218	117	60	174	177	82	22	1,102
(11)																				
1882		35	80	38	37	68	40	.....	298	3	50	161	188	107	85	163	120	37	9	923
1893	1	39	115	55	67	148	79	6	510	3	29	110	189	148	154	238	173	57	6	1,107
Mean .	1	37	98	47	52	108	60	3	404	3	40	136	189	128	120	201	147	47	8	1,015

wich magnetic declinations taken from day to day, where the hourly variation is eliminated. It can be shown that the declination is a component which vanishes in theory, and exists in practise only as a measure of the feeble variations of the earth's field which are distinctly accidental and only remotely connected with the solar action.

VARIATIONS IN LATITUDE IN THE 11-YEAR CYCLE.

We will now consider the prominences, spots, and faculae in the 11-year cycle in order to discover whether there is some evidence of a periodic variation in the latitude at which the output from the interior of the solar mass becomes visible to us. An inspection of the details of the three cycles contained within the interval of time 1872-1900, shows that there is a triple repetition of similar variations in these elements, and suggests that the mean values of the years similarly placed in the 11-year period may be taken as a close approach to the law underlying these cyclical changes. The means of Tables 1 and 2 are plotted on fig. 3. The scale denotes the frequency numbers as counted from the Italian observations,

and the zones are indicated by the degrees at the top of the chart. Dotted lines are drawn through the systems of the maximum numbers to mark the difference in latitude at which these develop. The prominences have two distinct maxima, generally, throughout the period, except that the one in high latitudes, 60°-70°, nearly disappears at the time of maximum spot frequency and the one in low latitudes, 20°-30°, practically disappears at the time of the minimum number of spots. After the minimum which has crests in high latitudes there is a vigorous recrudescence of the prominences in two distinct belts of maxima, 20°-30° and 40°-50°, with a tendency to diverge toward lower and higher latitudes; the higher varies 25° in latitude and the lower less than 10°. This swing in latitude of the maximum points is accompanied by a decided variation in the number observed, as indicated by the change in the areas included between the lines of prominence numbers and the axis of abscissas. The spots and the faculae have each only one maximum in the same hemisphere, which gradually approaches the equator from about latitude 25° at the time of recrudescence just following the maximum number. The dying

TABLE 3.—*Italian observations. Observed mean monthly distribution of the solar prominences.*

Rotation.	1872.	1873.	1874.	1875.	1876.	1877.	Mean.
1	202	150	91	37	13	40	89
2	229	200	135	69	51	75	127
3	214	130	140	60	51	59	109
4	157	188	93	55	26	37	93
5	219	180	97	65	51	55	111
6	229	139	107	45	42	95	110
7	281	215	96	48	47	54	124
8	315	229	105	124	107	115	166
9	287	105	111	131	114	82	138
10	143	190	163	51	105	42	116
11	129	89	75	71	83	31	80
12	130	98	115	46	88	54	89
13	110	140	35	54	59	3	67
14	.....	.....	52	.....	39	.....	.....

Month.	1878.	1879.	1880.	1881.	1882.	1883.	1884.	1885.	1886.	1887.	1888.	1889.
January	3	7	13	45	229	95	139	104	116	115	198	76
February	26	4	71	80	242	137	186	197	98	134	107	84
March	39	7	145	88	184	97	317	146	126	137	197	140
April	33	.....	54	109	146	133	212	111	82	129	266	49
May	31	12	81	210	183	183	237	226	162	127	181	19
June	27	64	146	177	269	122	237	351	174	257	117	20
July	59	57	260	299	288	219	364	328	233	268	154	62
August	22	61	137	284	249	167	399	221	162	231	222	99
September .....	.....	80	137	187	169	133	233	177	149	161	144	75
October	4	100	120	121	137	233	269	104	68	69	158	29
November	8	58	77	258	139	135	152	126	138	141	73	47
December .....	.....	40	97	140	92	142	111	193	77	108	70	24

Month.	1890.	1891.	1892.	1893.	1894.	1895.	1896.	1897.	1898.	1899.	1900.	Mean.
January	25	60	83	145	87	28	134	60	53	45	40	83
February	27	170	95	214	141	69	155	69	42	38	13	104
March	29	110	122	272	159	127	71	109	31	40	20	118
April	38	138	158	324	104	131	77	85	60	45	32	109
May	31	98	207	143	114	141	103	84	26	18	48	116
June	63	108	330	161	178	181	125	119	77	51	36	147
July	60	256	323	167	157	257	143	81	64	52	68	183
August	82	210	296	267	167	246	105	113	78	44	56	170
September	68	220	305	185	116	178	106	143	121	76	96	142
October	175	217	186	138	78	93	102	101	86	42	60	117
November	36	98	216	70	104	114	55	95	27	28	20	96
December	51	151	151	155	62	75	35	54	56	19	54	85

TABLE 4.—*Observed mean monthly distribution of the solar spots.*

Month.	1880.	1881.	1882.	1883.	1884.	1885.	1886.	1887.	1888.	1889.	1890.
January	15	20	28	29	56	26	8	6	7	.....	3
February	5	19	27	19	32	37	9	7	5	4	1
March	9	19	32	14	43	16	18	6	4	4	2
April	6	38	27	32	35	19	14	5	8	1	6
May	9	34	24	23	37	23	8	8	2	1	6
June	10	25	16	26	28	28	11	8	3	1	4
July	13	54	27	22	42	18	9	11	5	7	4
August	18	14	17	29	44	20	5	3	10	4	6
September	24	22	22	22	37	13	8	6	10	2	13
October	24	25	30	35	32	15	2	4	1	3	8
November	14	26	28	28	23	14	1	2	4	.....	3
December	11	23	20	34	23	7	3	5	3	7	5

TABLE 4.—*Observed mean monthly distribution of the solar spots—Continued.*

Month.	1891.	1892.	1893.	1894.	1895.	1896.	1897.	1898.	1899.	1900.	Means.
January	8	34	33	36	36	19	19	12	12	5	20
February	11	21	23	27	19	20	11	18	7	5	16
March	9	25	36	34	26	25	19	14	6	4	17
April	18	29	60	24	36	20	22	14	11	10	21
May	17	29	41	37	22	16	11	12	2	7	18
June	21	36	39	35	29	13	4	21	7	6	18
July	29	33	49	38	24	21	15	11	9	6	21
August	20	28	66	38	28	11	10	10	2	2	18
September	23	29	49	41	30	23	23	13	6	7	20
October	22	44	49	19	24	16	19	29	11	3	20
November	17	25	32	34	15	11	5	17	5	2	15
December	20	35	33	24	26	13	13	9	8	.....	15

TABLE 5.—*Observed mean monthly distribution of the solar faculae.*

Month.	1880.	1881.	1882.	1883.	1884.	1885.	1886.	1887.	1888.	1889.	1890.
January	34	52	64	60	81	57	18	12	17	1	21
February	53	59	81	54	73	82	16	16	7	1	12
March	109	87	92	45	74	64	30	20	17	4	13
April	29	123	76	57	61	42	25	9	14	4	7
May	47	150	80	61	50	58	40	15	8	6	15
June	57	128	79	56	67	63	40	24	12	7	12
July	74	181	116	39	68	41	32	15	14	12	14
August	81	141	80	58	64	46	13	14	18	24	17
September	136	161	64	92	66	56	18	9	24	12	27
October	115	102	50	101	47	22	9	7	8	11	12
November	86	85	62	86	50	31	5	12	9	2	16
December	87	72	79	84	47	32	12	16	12	10	17

Month.	1891.	1892.	1893.	1894.	1895.	1896.	1897.	1898.	1899.	1900.	Means.
January	8	52	68	79	54	56	63	83	34	73	47
February	37	42	76	76	38	61	60	67	70	45	49
March	30	56	87	53	70	68	65	78	31	71	55
April	43	71	91	57	88	89	83	62	39	76	55
May	52	75	119	68	49	75	69	132	48	52	60
June	63	97	107	103	87	62	89	94	56	95	67
July	75	94	125	88	90	83	91	132	83	68	73
August	64	59	94	86	68	82	116	138	98	146	72
September	46	84	85	86	66	68	68	97	12	97	65
October	51	92	78	74	60	66	72	57	14	76	54
November	37	65	65	96	75	40	95	45	51	38	50
December	48	75	112	75	46	52	75	59	46	100	55

spots of an old cycle in low latitudes very near the equator occur while a new series of spots is appearing in the higher latitudes. Fig. 3 tells its story so clearly that it is not necessary to describe it in greater detail.

We can bring out its meaning, however, in connection with the probable internal circulation from the interior of the sun more distinctly by constructing the movement of the maximum point of relative frequency in latitude during an 11-year cycle of the solar prominences, spots, and faculae, see fig. 4. The point on fig. 3 where the dotted maximum line crosses the line of relative frequency fixes the latitude of the maximum number. Hence, we take for coordinates the number from the scale of ordinates and the latitude from the abscissas (N, φ) and transfer these coordinates in succession from year to year to fig. 4. The first point in the prominence curve in the northern solar hemisphere is for the year 1894 ($N = 64$, $\varphi = 57^\circ$), and this is plotted at latitude 57° at the same scale distance from the solar disk, as on fig. 3 from the axis of abscissas, and marked 94, meaning the year 1894. The successive points mark the locus of the movement of this maximum in the 11-year cycle. The same method is applied to the two prominence systems of maxima in each hemisphere, and to the single maximum of spots and faculae in each hem-

isphere, respectively, the latter being plotted on the left-hand side of fig. 4 in order not to confuse the drawing. The diagram is to be interpreted as representing the variations of the maximum solar output in belts or zones extending around the entire photosphere.

It is instructive to note the regular course that this variation pursues, and this is of fundamental importance as indicating some characteristic conditions of the solar circulation. Beginning with the minimum years 1889 and 1890, the polar group of prominences rises rapidly until 1891, turns quickly toward the pole until 1893, then diminishes the number and gradually completes the circuit, with slow decrease of latitude, to 1899. The southern polar group maximum traces quite the same circuit, which has a considerable area and a peculiar lip at the years of minimum frequency. The equatorial prominence group begins in latitude 22° , rises quickly to a maximum height in the same latitude, lingers nearly in the same position for several years (1893–1895), with small decrease in latitude, and is followed by a gradual return to the beginning of the circuit. The same remarks hold true for both hemispheres. The equatorial area is long and narrow and the polar approximately equilateral in form, showing that the former changes less in latitude than the latter, the height being about the

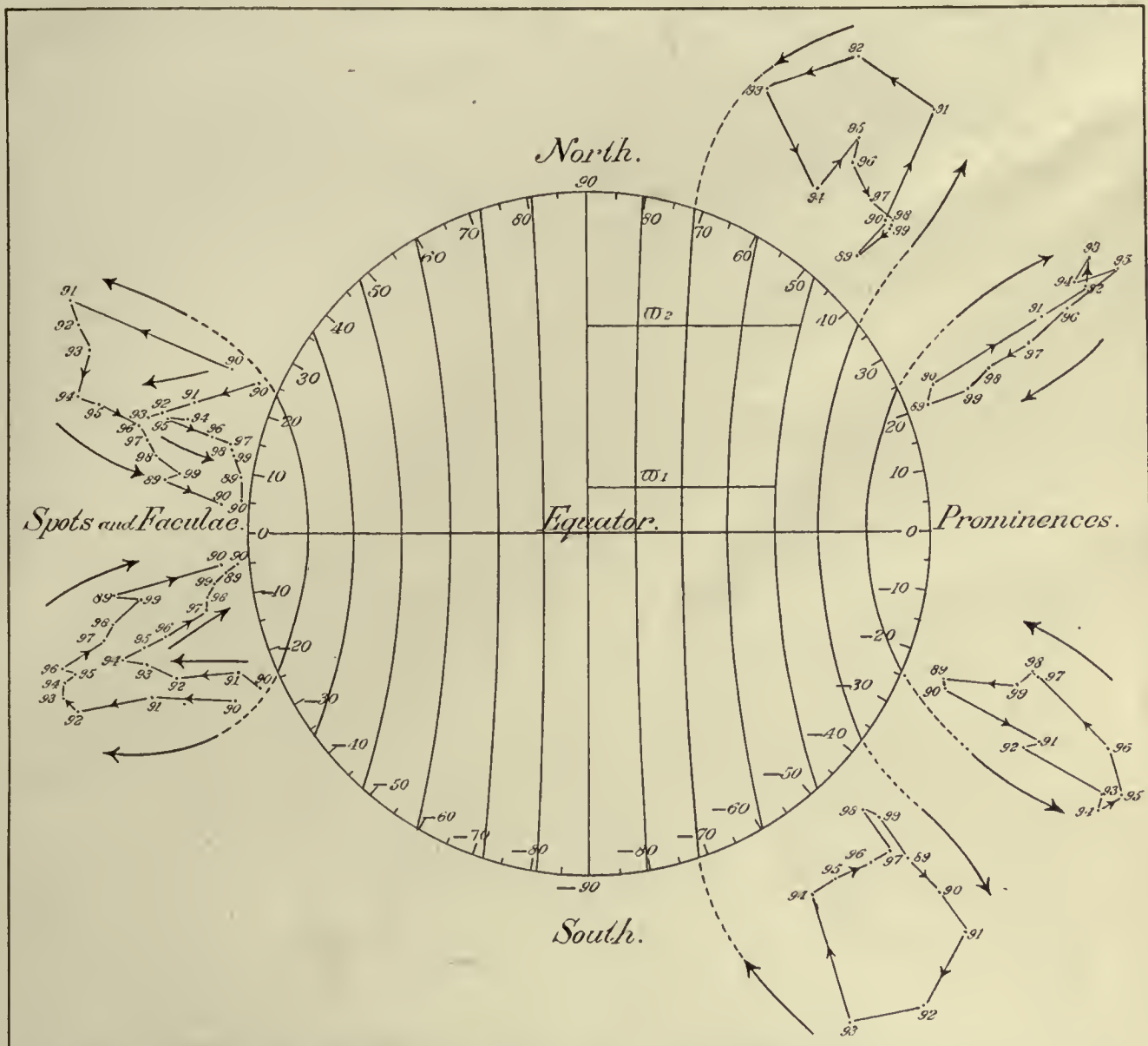


FIG. 4.—Movement of the maximum point of relative frequency in latitude during an 11-year cycle of the solar prominences, spots, and faculae.

same in each case. I have drawn some large arrows to show that a general movement outward is indicated for latitudes 22° to 45° at the recrudescence of the prominences, and that there is a movement inward in the equatorial and in the polar latitudes.

A similar construction for the faculae shows that after the minimum they also spring up powerfully to their greatest frequency in latitude 25° , and that they decline gradually with diminution of the latitude till they reach a minimum, where the characteristic double-belt occurrence takes effect. The spots construct a triangular area, well within that covered by the faculae, and they increase more slowly and decline more regularly than do the faculae, while the latitude is diminishing. The heavy arrows drawn on fig. 4 indicate an outward impulse in the middle solar latitudes and an inward movement nearer the equator. This result is in perfect harmony with that obtained for the prominences, and we can not avoid the conclusion that the sun in cooling emits energy and discharges material more vigorously in the middle latitudes than in the polar and the equatorial regions. This suggests the primary conditions of the circulation which prevail for a large mass like the sun cooling by discharge of matter and by radiation.

BIG—3

Care should be taken not to misinterpret the long arrows which have been placed upon fig. 4. These represent the direction of the rising of the maximum points to their highest positions and then the sinking back toward the surface. As shown by fig. 3 the entire solar surface is emitting outward, even when the arrow is pointing inward. Nevertheless, the movements of the maximum points in latitude and altitude must be attributed to an excessive output of energy, and this points to a fundamental circulation of the heat energy and of the material substances in the sun. The next problem in solar physics is to discover the laws that control this special variation of the distribution of energy.

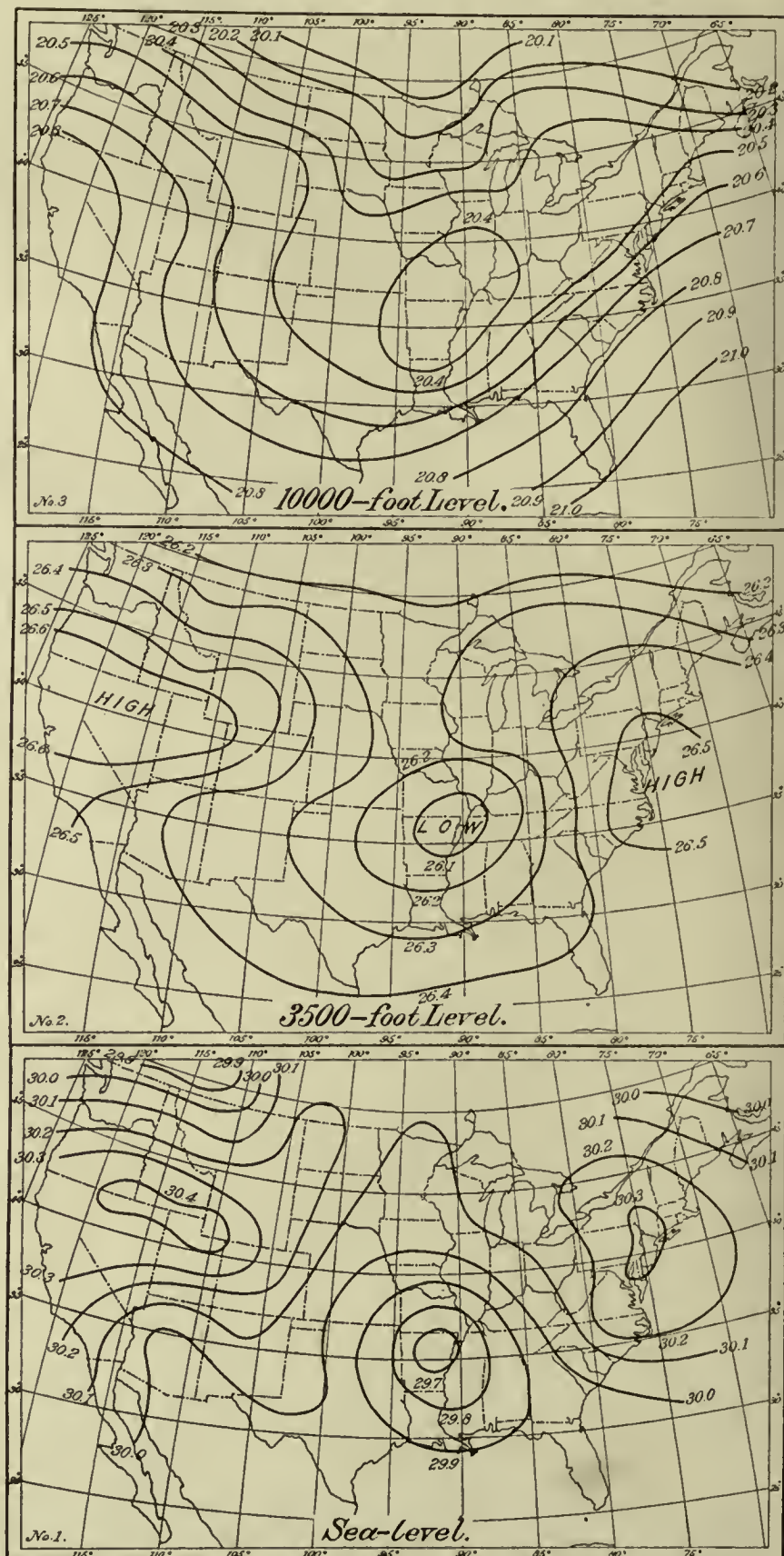
It is proper in this connection to reproduce the lines of the Helmholtz-Emden thermal structure, already noted in Bulletin I, Eclipse Meteorology and Allied Problems, p. 71. The interior curves computed from Helmholtz's equations harmonize so happily with the exterior lines derived from this discussion on the output of the sun, that the probability is strengthened that this scheme is the proper one with which to enter upon the analysis of the internal circulation of the sun. As already noted in that bulletin, if the vortex law ($\omega r^2 = \text{constant}$, where $\omega = \text{the radius}$ and $\omega = \text{the angular velocity}$) holds

good in this case, then we have an explanation of the cause of retardation of the diurnal angular velocity of the motions of the photosphere in middle latitudes as referred to the equatorial or polar belts. For if $\omega_2 > \omega_1$, then $\omega_2 < \omega_1$, and since ω_1 is the initial rotational velocity at the equator, the angular velocity in middle latitudes must be less than at the equator or at the poles. This agrees with the result of the surface observations. Furthermore, the equatorial angular velocity is probably that of the interior mass, or nucleus of the sun, and the poles should have the same velocity, a result in harmony with that deduced from my discussion of the terrestrial magnetic field. This equatorial and polar angular velocity gives a 26.68-day synodic period for the rotation of the sun. Finally, the middle latitudes must give a slower angular velocity and a greater period, such as 27.30 days in the belts 12° to 15° .

Since the mass of the sun ought not by this theorem to have in any portion of it an angular velocity less than that of the equatorial plane, it does not appear to be reasonable that the short periods of about 25.80 to 26.00 days, which several investigators have announced as that of the sun's rotation derived from a discussion of several different terrestrial phenomena, can be correct. It is very difficult to perceive how there can be any basis for a period shorter than 26.68 days; on the contrary these authors seem to find a period at least one day shorter than the quickest period that can be derived from the observations and discussions of surface solar phenomena. It is very probable that the problem of the circulation within the sun must be worked out before we can hope to bring that of the rotation of the solar mass to a satisfactory understanding.

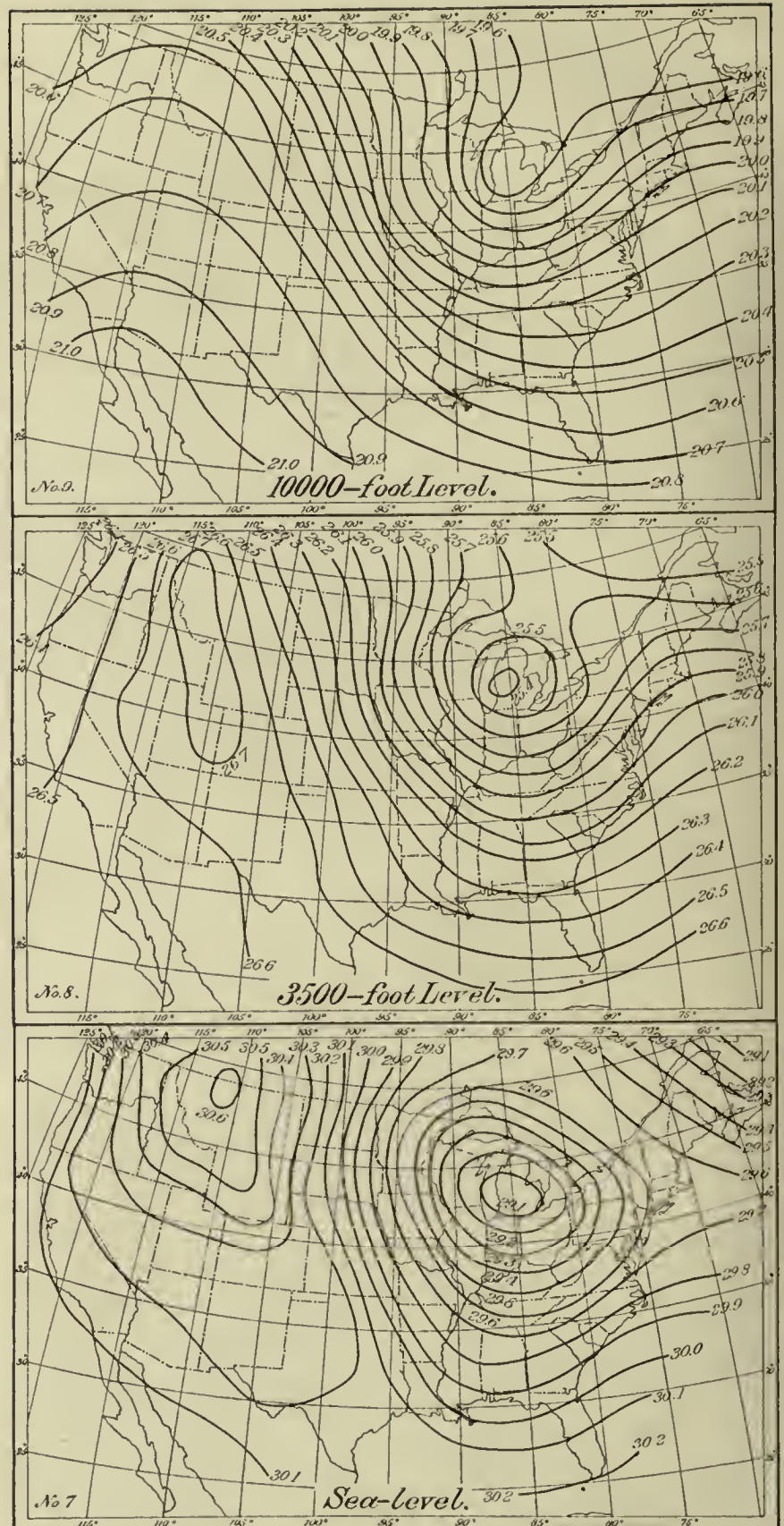
III.—THE STRUCTURE OF CYCLONES AND ANTICYCLONES ON THE 3500-FOOT AND 10,000-FOOT PLANES FOR THE UNITED STATES.

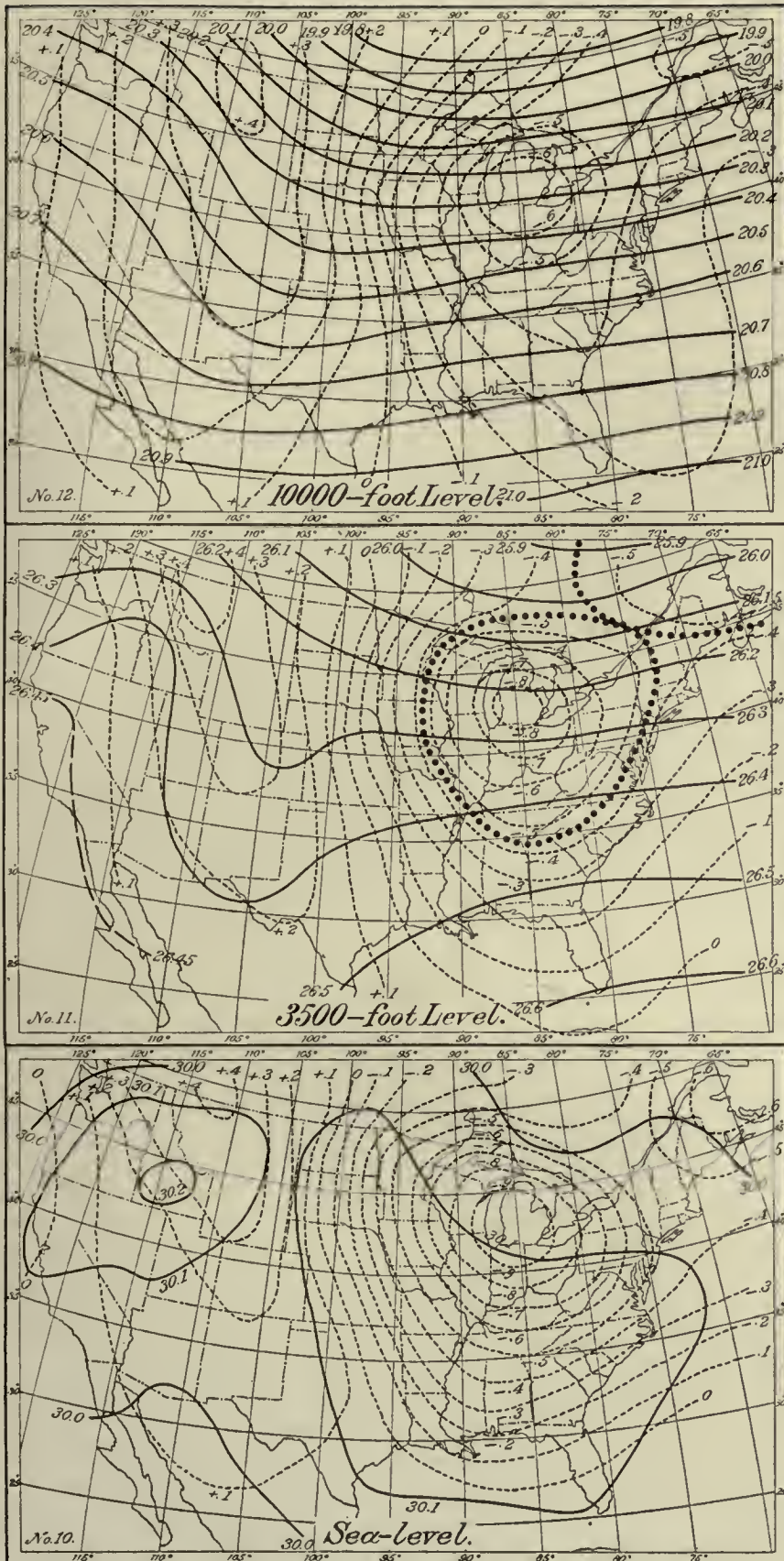
The reconstruction of the theory of cyclones and anticyclones depends upon the determination of the velocities and directions of the air movements, the form of the isobars, and the distribution of the isotherms at several planes above the sea level. My report on the International Cloud Observations of 1898-99 gives the result of the survey of the upper air for the vectors of motion; this was supplemented by a series of papers in the MONTHLY WEATHER REVIEW, January to July, 1902. My report on the Barometry of the United States, Canada, and the West Indies, 1900-1901, has provided the necessary means for reducing the observed station pressures to three standard planes. The observational requirements of the problem will be completed by the discussion of the temperatures and vapor tensions, which has been already begun, though it will take considerable labor to finish the research. Meanwhile, it is profitable to make use of the material at hand in a series of studies on the circulation of the atmosphere at different levels up to two or three miles above the sea level. Beginning with January, 1903, the successive MONTHLY WEATHER REVIEWS will contain charts showing the mean monthly isobars on the sea-level plane, the 3500-foot plane, and the 10,000-foot plane. By comparing these pressures with the series of normal pressures given on the charts of chapter 7, Barometry Report, we can find the departures for each month on these three planes, and a discussion of such departures from year to year, when studied in connection with other phenomena, will have an important bearing upon the discovery of the laws for use in seasonal forecasting. Similarly, monthly temperature charts are given, and these are constructed by means of the temperature gradients which can be obtained from the data in Table 48, of chapter 8, of the same report, by subtracting the values of t from t_0 (sea level), t_1 (3500-foot), t_2 (10,000-foot) in succession. The latter temperatures were found by a process which eliminated the local abnormalities contained in the observed station temperatures, and they have permanent value. The surface temperatures of the several stations need to be further revised, and so we can claim at present for the temperature gradients only an approximate correctness. This imperfection will not greatly influence the position of the mean isotherms, but the reduced temperatures of neighboring stations do not appear on the maps quite as harmonious as we hope to make them by means of the revision just mentioned.



January 2, 1903.—Charts 1, 2, and 3 are transcripts of the isobars as derived by computation in accordance with the system contained in the Barometry Report. We note (1) that the closed isobars of the cyclone at sea level tend to diminish in number and intensity at the upper levels and that they finally open out into shallow, inflected curves at the height of about two miles; (2) these curves in opening out first form cusp-shaped curves, joined together by a pressure which is higher than that north or south of it, whereby one closed isobar and one long or open isobar of the same name occur above and below the line of the cusps; (3) the high pressures to the east and west of the cyclone diminish in area and soon fade away into the long, looping isobars of the upper strata.

We now find the general normal and the local departure components of these observed isobars as follows: (1) The normal isobars for the month are copied on tracing paper in black lines, being extracted from the January charts of chapter 7; (2) these lines are laid over the observed isobars, and a new system of lines is constructed by tracing the diagonals of the quadrilateral figures thus formed, and these new lines are shown in red lines on Charts 4, 5, and 6. These curves give us in tenths of an inch the values of the local pressure disturbances which deflect the normal isobars, and they therefore measure the pressure effect of the local cyclone proper. The causes that produce these local departures of pressure must be the same as those that produce the cyclone itself. We may assume that the upper vectors of motion are parallel to the observed isobars, and we conclude that in this particular storm a current of air from the southeast is flowing upon the United States; that a part of it curls to the left and enters the vortex of the closed isobars, which generates a vertical component, and that the rest of this stream flows away by uniting with the normal general circulation. There seems to be also a minor stream of air from the northwest, and a portion of this enters the vortex.





January 7, 1902.—Charts 7, 8, and 9, are transcripts of the reduced pressures obtained in the same way; Charts 10, 11, and 12 give the normal monthly isobars, and the local isabnormals of pressure of a typical cyclone central in the Lake region. Here, again, the central closed isobars open out first into cusps with a feeble high pressure bridge, and then into loops which become flatter with the height, and finally disappear by merging in the normal lines. It is apparent that on the west side of the center a strong current from the north is chiefly concerned in building this cyclone, a part of it curling into the central vortex which has a vertical component, the remainder escaping eastward into the normal circulation. By comparing the vectors of Chart 23, International Cloud Report (blue arrows), we see that those vectors conform very closely to these isobars, and that they are generally parallel to each other. The component vectors of figs. 6 and 7, MONTHLY WEATHER REVIEW, March, 1902, show that the deflecting vectors also follow closely parallel with the isabnormals of pressure. The agreement of these three independent researches assures us that the analysis of the structure presented in my previous papers harmonizes closely with the observed facts. It is evident that if a series of coaxial circles about the center of the cyclone be superposed upon a system of parallel lines representing the general isobars, we should obtain resulting curves similar to those that have been produced by reduction of the pressures from the surface data. This involves an equation of three degrees and three characteristic areas, one central, one above the cusp lines, and one below them. (Compare fig. 11.) This analysis will therefore enable us to pursue the mechanics of cyclones into remote details, and so we shall at length be able to compare theory and observation with much precision. The subject will be further illustrated and discussed in later papers.

IV.—THE MECHANISM OF COUNTERCURRENTS OF DIFFERENT TEMPERATURES IN CYCLONES AND ANTICYCLONES.

THE WEATHER BUREAU CLOUD OBSERVATIONS.

The report on the international cloud observations of May 1, 1896, to July 1, 1897, Report of the Chief of the Weather Bureau, 1898-99, Vol. II, contained an outline description of a theory of the structure of cyclones and anticyclones, which was thought to be indicated as the probable interpretation of the motions of the air in cyclones and anticyclones. It was evident that a more complete insight into the mechanism of this type of motion in a fluid under atmospheric conditions would be afforded by the construction of systems of isobars on at least three planes having different elevations. For this purpose the sea level, the 3500-foot level, and the 10,000-foot level were selected, and suitable reduction tables have been made as described in the report on the barometry of the United States, Canada, and the West Indies, Report of the Chief of the Weather Bureau, 1900-1901, Vol. II. Since December 1, 1902, we have received daily reduced pressures on these planes from the regular stations of the United States and Canada, and the corresponding charts have been drawn with care by Mr. George Hunt of the Forecast Division. A definitive treatment of the problem evidently requires charts of the isotherms on the same planes, but it will not be necessary to wait for the completion of our discussion of the temperatures, because we have already obtained the approximate gradients needed in a preliminary study of this question. It is proposed to summarize the present status of the research, previous to working out an analytic treatment of the mechanism of tornadoes, cyclones, hurricanes, and the general circulation, from the data now in possession of the Weather Bureau.

THE GENERAL CIRCULATION.

The circulation of the atmosphere has been analyzed by meteorologists into (1) the general cold center cyclone, which covers a hemisphere of the earth from the pole to the equator, and (2) the local warm center cyclones and the anticyclones, which drift eastward in the temperate latitudes. Ferrel worked out his well-known canal theory for the general cyclone, with northward motions in the upper and southward motions in the lower strata of the atmosphere. This theory was adopted by Oberbeck and carried out with difference of details, and it has been the prevailing view till the discussion of the Weather Bureau observations of 1896-97 in the United States proved that it is incorrect and must be greatly modified. No northward movement of importance exists in the upper strata, and there is no calm belt separating the eastward drift from a westward current in the polar zone. In the Tropics the motions are substantially those deduced by Ferrel, and they result naturally from the equations of motion on a rotating earth heated in the equatorial belt. Professor Hildebrandsson's report on the International Cloud Observations confirms these facts for Europe and Asia generally, and therefore we conclude that they are fundamental, and that the canal theory must be finally abandoned. The Weather Bureau report showed that the incoming solar radiation of short waves heats the atmosphere only a little, but that it does heat up the earth's surface. This latter radiates much longer heat waves at terrestrial temperatures, and thereby the lower strata of the atmosphere are heated up by convection currents to a distance of two or three miles. This heat energy is very vigorous in the

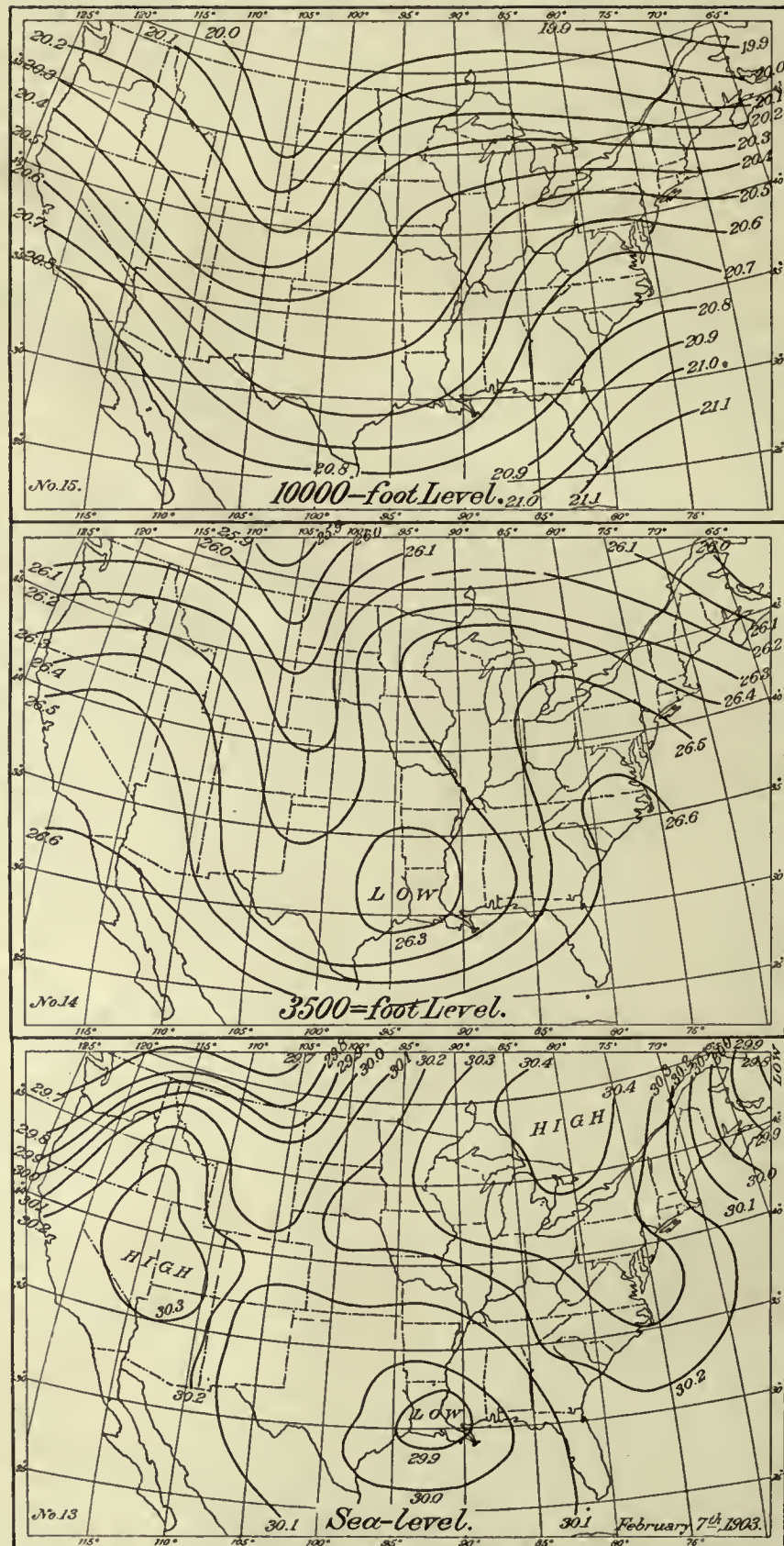
Tropics, and produces currents of warm air which leak outward and flow toward the poles only in the lower strata instead of in the high levels, determining by their motion the local distributions of pressure near the surface of the earth. By an analogous process cold currents flow from the higher latitudes toward the equator at low or moderate elevations. These counter currents meet in the middle latitudes, as over the United States, and we have now to study the action of the resulting mechanism.

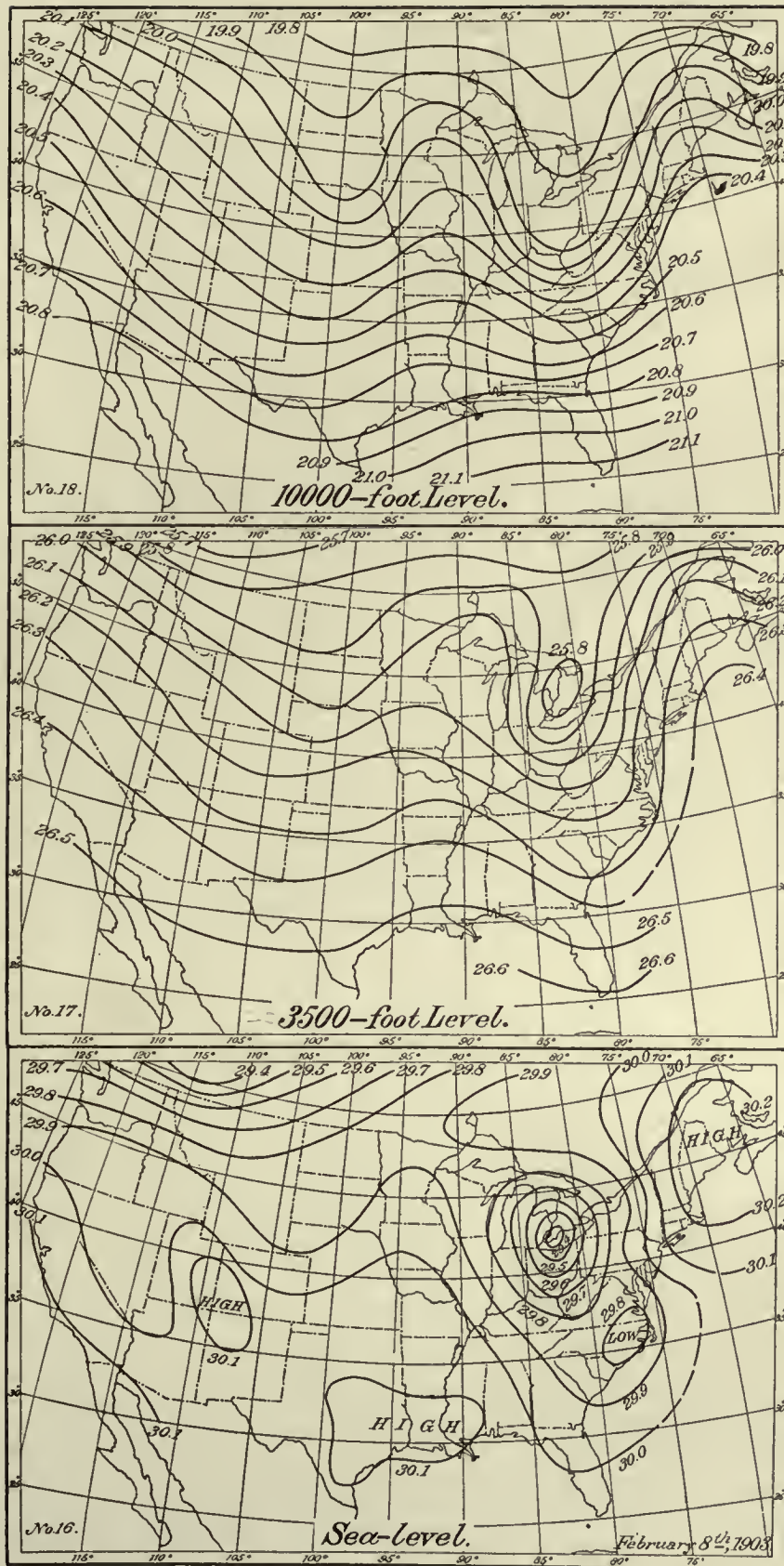
THE LOCAL CIRCULATION IN CYCLONES AND ANTICYCLONES.

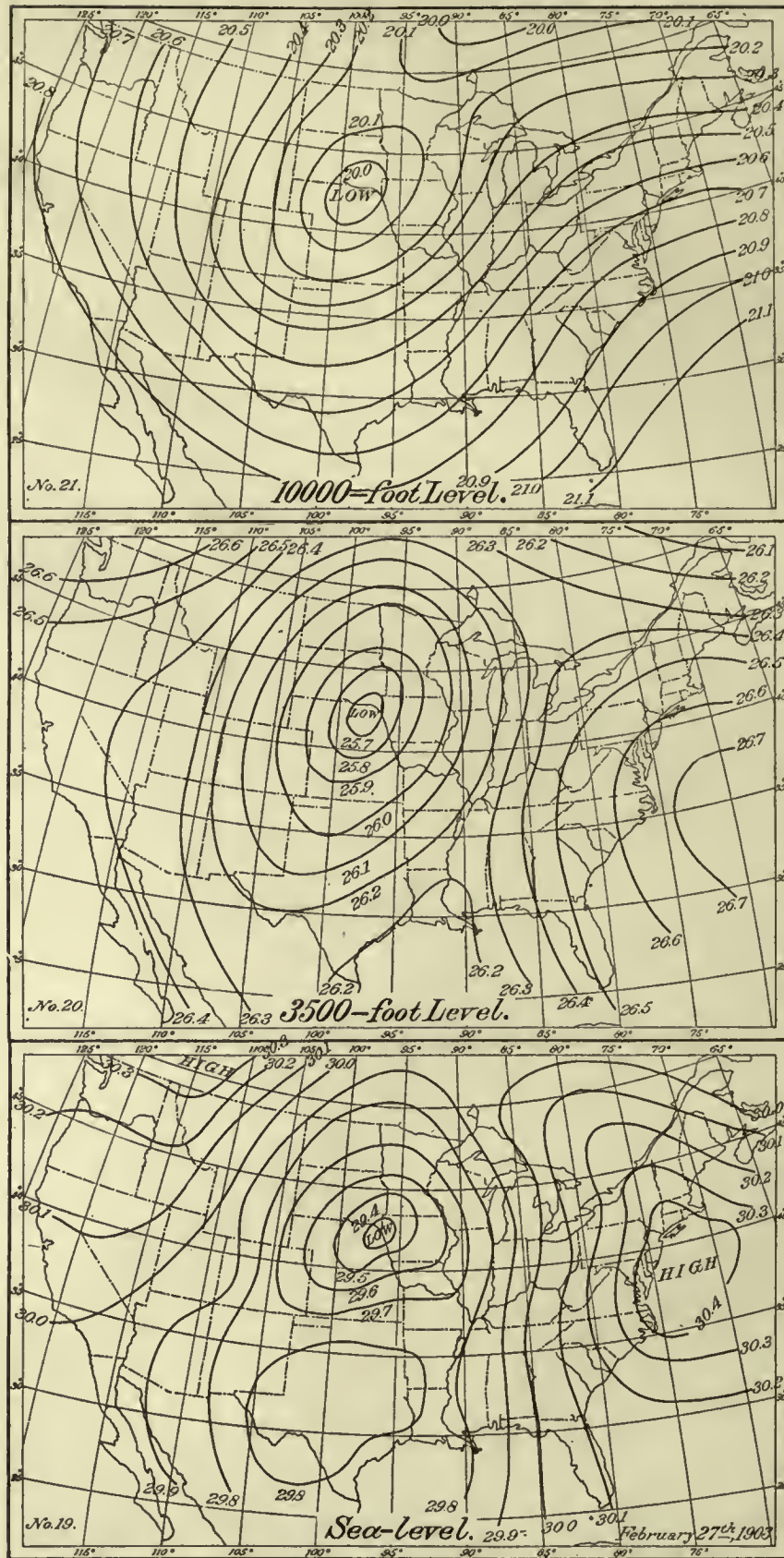
In order to account for the phenomena observed in cyclones and anticyclones, there have been two distinct lines of discussion, (1) the thermodynamic theory and (2) the hydrodynamic theory. The former required a warm central current of rising air to form a vortex. The Espy hypothesis, that the heat necessary to drive the vortex is derived from the latent heat of condensation evolved in changing aqueous vapor into water of precipitation, has been strenuously maintained by many students. There are, however, numerous serious objections which can not be set aside, and these have caused during the past few years a general abandonment of the theory as a true account of the primary cause of cyclones. Ferrel worked out his theory by means of a special type of vortex with closed boundaries, but this does not, unfortunately, in the least satisfy the observations, and it has been rejected as the result of such discrepancy. The equations of motion admit of solution by a different vortex, which more nearly conforms to the requirements of the problem, but no driving force sufficient to sustain a cyclone was discovered before the one suggested by the Weather Bureau research, so that up to recent times the local vortices remained to be fully accounted for on a sound physical basis. The second theory of the local circulation considers it as simply a question in hydrodynamics, where the local thermal force is subordinate to the driving action of the great whirl which gyrates about the pole as a center. In this view the eastward drift simply curls up at places and forms eddies in the great current, and they are borne along by it. This seems to be the general idea adopted by Professor Hildebrandsson in his recent report. There is undoubtedly a certain amount of dynamic action which enters into the construction of cyclones, but there must also be a powerful mechanical force derived from the effort to restore the thermal equilibrium between currents of different temperatures. We shall, therefore, endeavor to trace out these processes more fully than it was possible to do a few years ago and explain a very probable theory of the interaction of the forces that generate and sustain these local storms.

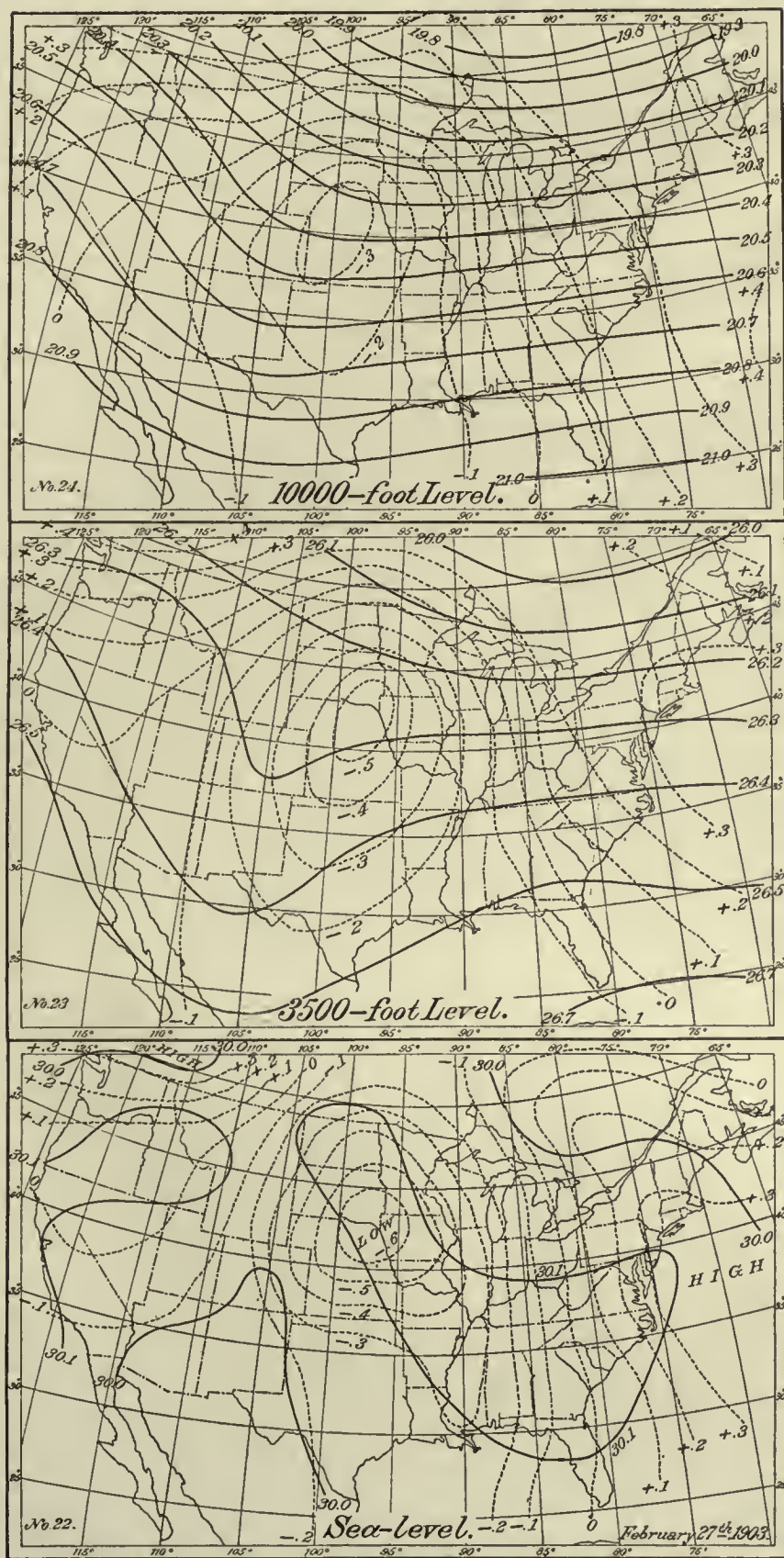
THE ISOBARS AND STREAM LINES ON THE SEA-LEVEL PLANE, THE 3500-FOOT PLANE, AND THE 10,000-FOOT PLANE.

It is first necessary to recall briefly the results derived by the Weather Bureau in its research into this problem. A consideration of the available meteorological observations above the surface of the ground convinced me that it would be necessary to depend upon computations rather than upon direct observations, in order to obtain the daily synoptic pressures and temperatures upon any given reference plane. Observations by balloons, kites, theodolites, or nephoscopes are indis-









pensable in order to secure the necessary data for making the reductions and for checking the results, but it is not possible to make observations on any elevated plane in sufficient numbers to construct a daily map of the weather conditions without adding many laborious corrections. It was, therefore, apparent that suitable methods of computation must be devised for this special purpose in order to reduce the problem to practise. The Weather Bureau now possesses complete barometry tables for the isobars on three planes, and is working out the data for the corresponding isotherms. We have, however, approximate temperature gradients which can be used for the present, in all the preliminary discussions. The thermodynamic formulæ for the $\alpha, \beta, \gamma, \delta$ stages have been adapted to tables for the computation of B, t, e at different elevations. It was indispensable to substitute these tables for the Hertz diagram, because that is liable to an error as large as 7 millimeters, owing to the neglect of the vapor tension in evaluating the numerical data. Since we require vertical gradients of pressure to within 0.01 millimeter, it is practically impossible to secure that degree of accuracy if the vapor tension is rejected.

In the MONTHLY WEATHER REVIEW for January, 1903, charts of the isobars, figs. 1 to 6 for January 2, and figs. 7 to 12 for January 7, are given on the three planes; the two components into which they were resolved are also charted, namely, the normal isobars for the month, as given on Charts 28, 30, and 31 of the Barometry Report, and the local disturbing isobars, which are approximately circular in form at the center, the other lines having special curvatures which will be explained. In the present paper there are similar charts, figs. 13 to 15 for February 7, 16 to 18 for February 8, and 19 to 24 for February 27. In order to resolve the observed isobars into the components, the normal isobars of the month were copied on tracing paper; these were superposed upon the computed isobars of the given date, and the diagonals were then drawn to form the second system of components. Attention should be fixed upon one characteristic feature in these charts of isobars, which is readily recognized on nearly every map. To the north or northeast of the closed isobars around the low center, there is a cusp-shaped set of isobars forming a saddle between two isobars of the same name; thus, on fig. 19, the cusps 30.0 between isobars 29.9; on fig. 20, 26.4 forms the cusps of a saddle between 26.3; and on fig. 21, 20.2 forms the cusps to 20.1.

By referring to Maxwell's Electricity and Magnetism, Volume I, Plate III, an analogue to this typical construction in electrostatics is to be found; his Plate I is an analogue to a cyclone in relation to the general circulation around the pole, and Plate II is an analogue to an anticyclone. These figures are constructed by the precepts on page 169, so that the resulting isobar is by analogy $B = B_1 + B_2$, where B_1 refers to the general isobars and B_2 to the local isobars. In the electrostatic analogue the potential is found by the law $V = \frac{e}{r}$, where the

successive values 1, 2, 3 are assigned to V , and r is computed from a given value of e . In the case of the isobars, the differences are nearly equal to each other in the general system, and in the local system the gradients may be taken, for example, about twice as great. Specifically, on the normal charts the pressure difference is $G = 0.1$ inch for about one and three-fifths degrees in latitude, or 180,000 meters, or 112 miles. A vigorous cyclone is formed by superposing about eight circles, with the gradient $G = 0.1$ inch for four-fifths of a degree, or 56 miles. The irregularities arising from the distortion of either typical system give rise to problems on the conditions of cyclones and anticyclones which are of much interest. In the case of electrostatic force we deal with potentials and lines of force; in that of pressure with stream lines and gradients, since in the frictionless upper strata of the atmosphere the lines of motion are parallel to the isobars unless under special dynamic conditions. Now, on Charts 36 and 39, of the Cloud Report, are

shown isobars after Teisserenc de Bort, drawn about the pole at the elevations 1500 and 3000 meters, respectively. This corresponds with the system of large circles in the electrostatic analogue. On Charts 30 and 31, of the Barometry Report, giving the normal pressure for the 3500-foot and the 10,000-foot planes, we have constructed the lines accurately for one special area in the general system of isobars, namely, that covering the United States, and these are similar in form to those from Teisserenc de Bort, though numbered differently in the inches on account of changes in the adopted heights. They are drawn as perfectly as possible and may be trusted to represent the result of eliminating the local cyclonic circulations.

The maps of pressure and temperature given as Charts VIII and IX of the MONTHLY WEATHER REVIEWS for January and February, 1903, agree closely together in their curvature relative to the pole. By comparing with these high level isobars and isotherms the wind directions determined for the upper cloud system, as shown on Charts 20 to 35 of the Cloud Report, it is possible to infer that the stream lines of the general circulation are parallel to the lines of equal pressure and temperature in the higher strata of the atmosphere. The divergences from this system, which occur at any place, are, therefore, not due to the action of the forces of sliding friction such as produce eddies, but to the interplay of dynamic forces of motion derived from other sources. Furthermore, it is simpler to determine the direction of these common lines, the isobars, isotherms, and vectors of motion in the upper atmosphere by computing the isobars and isotherms from the surface data than by the laborious compilation of wind directions and velocities by means of cloud observations, from which the resultants may be deduced. That is to say, we may have daily stream lines on the upper planes by computation from surface data, which are as reliable as those which would be obtained from a long series of cloud observations reduced to annual or monthly means. This is a practical conclusion of much value in meteorology. The isobars on Charts 37, 38, 39, 40 of the Cloud Report, from the data of Teisserenc de Bort, show that there is a greater density of the gradient lines from latitudes 25° to 60° , than nearer the equator or the poles. Therefore the pressure gradient is stronger over the United States than in the tropical or in the polar zones. Such a diminution of the general gradient in lower latitudes is in accord with that theory of the general circulation which drives the currents westward in the lower strata of the Tropics; in the higher latitudes the decrease in gradient indicates a feeble tendency to form a belt of winds flowing westward near the pole. It is a tendency only, because the gradient does not reverse but continues to diminish to the pole, and the motion is everywhere eastward. This is another fact in contradiction to the canal theory, and it also implies that the return circulation of cold air from the poles to the Tropics sets in near the latitudes of 50° to 60° in the descending anticyclonic structure, where the cold streams originate in connection with local areas of high pressure, rather than in the polar zone. The cyclones and anticyclones in middle latitudes are the natural products of the thermal interchange of heat between the "sources" which are in the warm currents and the "sinks" which are in the cold currents. This is not brought about through cooling a northward current in the highest strata of the atmosphere by its radiation of heat into space, or by vertical expansion in the Tropics, as the canal theory requires. The hot and cold masses of air, so far as they are produced by the differences of insolation in the lower layers of the atmosphere, are brought together into physical contact through the low level countercurrents, which are the winds from the south and from the north, respectively. These currents of different temperatures form the natural equivalents to the boiler and the condenser in a thermal engine, and the Carnot cycle is applicable to the analysis of the cyclic processes. The stream lines observed in the motions of

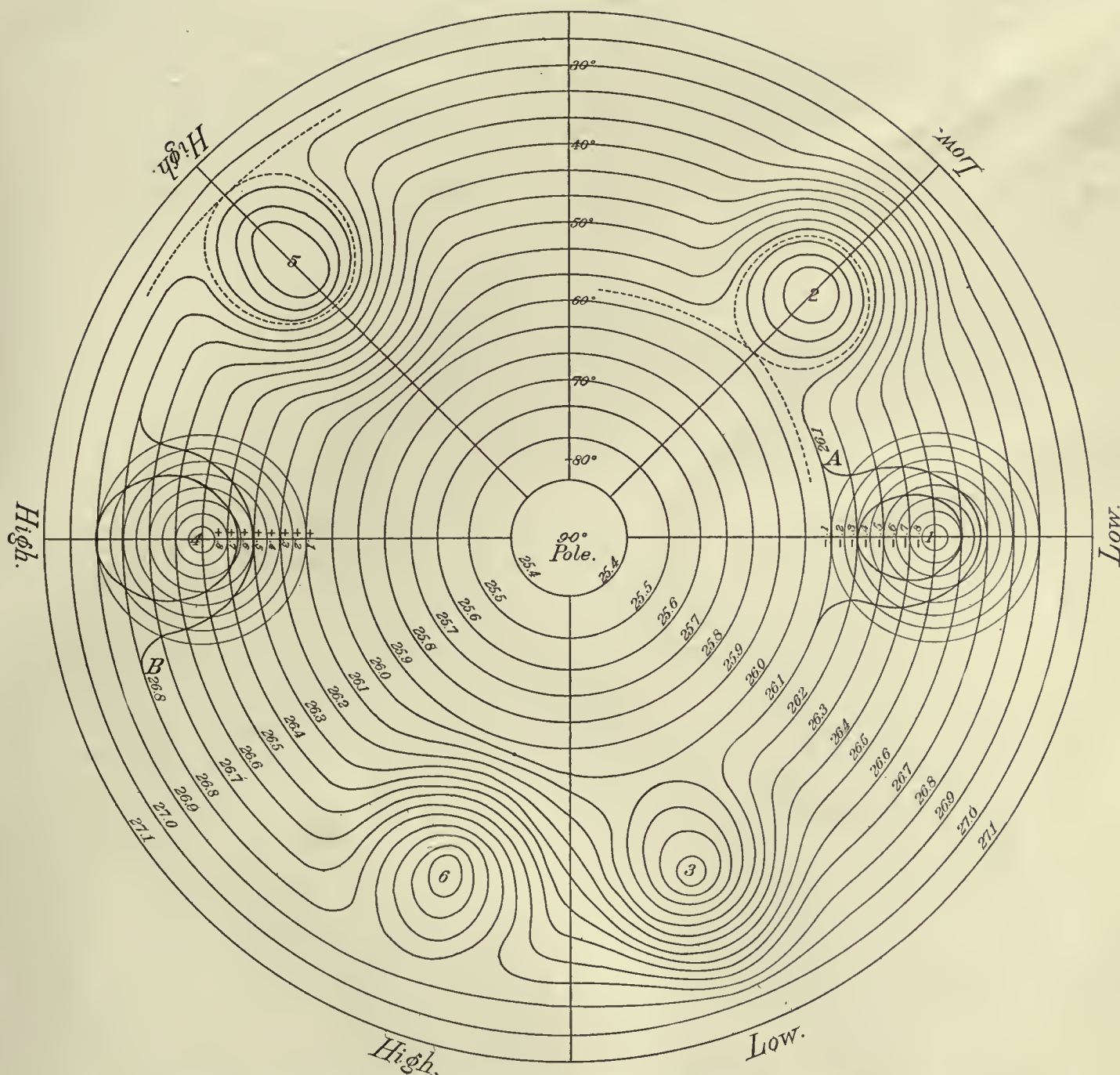
Latitude 20° 

FIG. 25.—The formation of local anticyclones and cyclones in the general circulation about the poles.

the atmosphere as local circulations are built up by the struggle there going on to restore the thermal equilibrium and uniform temperatures. This countercurrent theory is an effective one, in that it brings the abnormal temperatures of the atmosphere into contact through the streams of different temperature, so that they can work mechanically upon one another. The canal theory keeps the currents separated throughout the entire circuit, so that the assumed cooling and heating in the circuit is more like the local heating of a closed current at one portion, while it cools in traveling through the remainder of its course. There is little mechanical efficiency in that process, and it is not useful as a meteorological theory, nor in accordance with the facts of observation.

A certain average excess of heat in the Tropics is required

to keep the general cyclone moving at its observed rate of gyration in the upper strata. The thermal equator of such motion moves annually in latitude northward and southward, and this carries with it the entire thermal engine in its annually changing configuration. In the northern winter the thermal equator is far to the south, the contrast between the north polar cold and the tropical heat is much increased, and the general cyclone is relatively efficient; in the northern summer the thermal equator is far to the north, the difference of temperature between the boiler and the condenser of the northern engine is less, so that the circulation is relatively feeble. This oscillation of the heat energy northward and southward, carrying with it the thermal structure toward one pole or the other, just as the astronomical zones of day and

night move up and down the earth in latitude, is depicted in the series of diagrams of normal pressure shown in Charts 28 to 31 of the Barometry Report.

The corresponding variations of the temperatures are given on Charts 18, 19, 20, and of the vapor tensions on Charts 23, 24, 25 of the same report. The functions of B , t , e , which are involved in these variations, constitute the basis for a complete solution of the forces that generate and maintain the general circulation in middle latitudes. If we could extend this system of pressure and temperature charts to the pole, and to the equator on the American Continent, and also obtain the vectors of motion, it would afford the required data for the discussion of the dynamics involved in the circulation of the entire atmosphere, and this is the ultimate problem of our meteorology.

The variations of this general circulation from season to season should be extended to include its average changes from year to year, and also the connection of these with that part of the solar energy which is expended as radiation, and is variable in long and short cycles. This will form a science of cosmical meteorology upon which long range forecasting of the seasons can be based. Unless the subject proves to be too complex for human skill to classify, we shall eventually construct a meteorology rivaling other branches of astrophysics in interest and value to mankind.

THE MECHANISM IN CYCLONES AND ANTICYCLONES.

Turning now from these considerations regarding the general circulation to the mechanism of local circulations, we will further illustrate the separation of the local components from the general normal isobars by the six diagrams of fig. 25, the formation of local anticyclones and cyclones in the general circulation about the pole. We draw 18 concentric circles about a pole as a center, where the common difference is 5 millimeters, except in the polar zone where the difference is greater. The outer circle extends to latitude 23° , that is to Havana, so that these circles cover the latitudes in which the cyclones are produced in northern latitudes. Diagrams 1, 2, 3, show the method of constructing a low pressure area, and 4, 5, 6, that for a high pressure area; diagrams 1 and 4 give examples of the drawing of a few individual resultant curves; 2 and 5 are complete for isolated low and high areas; 3 and 6 exhibit the connection between a high and a low area, and this diagram is comparable with the isobars found on the charts of reduced pressures, as figs. 13, 14, 15, 16, 17, 18, of this paper. In making these specimen diagrams a system of local circles is superposed upon the general circles, but the common difference between them is taken half as much linearly, that is the gradient is twice as steep. On the general circles 5 millimeters is equivalent to 0.10 inch of pressure, on the small circles 2.5 millimeters is equivalent to 0.10 inch of pressure. These relative dimensions serve approximately to illustrate a strong winter cyclone, but they should be modified according to the observed conditions of the individual cyclone. When the monthly normal isobars are subtracted from the observed map of a given day, we have at once the small circular system, together with its variations from the normal type according to the prevailing circumstances. Looking at diagram 1, of fig. 25, we see that in passing from the pole outward each circle is $+0.10$, one-tenth inch higher, beginning for example with 25.4 and extending to 27.1. The small circles are numbered $-.1$, $-.2$, $-.3$, . . . for the low area, and $+.1$, $+.2$, $+.3$, . . . for the high area. At the point A we have 26.1 on the large circle; on the next circle it becomes, $26.2 - 0.1 = 26.1$, by uniting the two gradients; on the next it is, $26.3 - 0.2 = 26.1$. In this way, drawing the diagonal lines, we pass around a U-shaped curve having a certain concavity. Other curves are formed outside and inside of it, a few of the inner curves making closed ovals, ec-

centric to the center. The dotted curve on diagram 2 shows where the cusp-shaped curves unite over the saddle of higher pressure. The diagrams 4 and 5 are drawn in a similar way, by using the plus system of circles. At B we have $26.7 + 0.1 = 26.8$; $26.6 + 0.2 = 26.8$; $26.5 + 0.3 = 26.8$ Similarly the other lines are drawn. Finally, in diagrams 3 and 6 the two systems are united, so that the lines flow from one to the other continuously. It should be noted that in fixing the centers of the two systems of component coaxial circles, that for diagram 3 was placed on the isobar 26.5, and that for diagram 6 on the isobar 26.4. That is to say, the center of the anticyclone must be nearer the pole than that of the cyclone, in order to make the isobars continuous, otherwise some of the ends of these systems of high and low areas are left unconnected and without natural continuity.

A comparison of these typical isobars with those constructed from the daily observations, see figs. 1 to 24, proves conclusively that they are substantially of the same type. We find the cusp formation on each with the opening of the U-shaped figure toward the pole in the cyclone, but toward the equator in the anticyclone. The closed curves of the cyclone are more nearly elliptical than those of the anticyclone, as is commonly the case on the weather maps. The flow of air from the northern quadrants of the anticyclone toward the southern quadrants of the cyclone is necessary to the structure.

COMPARISON WITH OTHER OBSERVED CONFIGURATIONS.

In order to recall the results of the research which are included in the Cloud Report, the following drawings are introduced. Fig. 26 shows the vectors of motion and their components as observed in anticyclones and cyclones at the 1000 meter (3280-foot) level, and the 3000 meter (9843-foot) level, so that these are comparable with the isobars computed on the 3500-foot and the 10,000-foot planes. The direction of the original vectors is evidently parallel to the isobars, the long vectors which indicate greater velocity are to the north of the anticyclone where the isobars are closer, and then to the south of the cyclone where the closeness of the pressure lines is a maximum. Comparing the anticyclonic and cyclonic components with the resolved local isobars on the charts of observed pressures, figs. 1 to 24, the opening of the stream lines marked A on the cyclone corresponds with the opening in the U-shaped clone, similar conditions are found to the south of the anticyclonics. Furthermore, in fig. 27, I, II, III, three charts are reproduced from the Cloud Report; Chart 23, the mean winter Lake region low; Chart 29, the mean west Gulf low, each for the lower clouds; and Chart 35, the mean summer hurricane low for the upper clouds. The stream lines flow uninterruptedly to the center on spiral or disturbed spiral curves, one stream from the northwest and another from the south, and to the north of the center the same U-shaped cusp formation is described by the vectors of motion as are found on the charts of isobars. It is remarkable that in the case of the hurricane this formation is found in the cirrus levels, just such as in ordinary cyclones is produced in the cumulus levels, showing that this fundamental typical construction penetrates to the height of 5 or 6 miles, when the forces of motion producing it are sufficiently intense. The relative penetrating power of the cyclonic action is a very important feature, which is brought out by these isobars and stream lines in the higher levels.

Furthermore, consider the component local isobars in dotted lines on figs. 4, 5, 6, for January 2; 10, 11, 12, for January 7; 22, 23, 24, for February 27. On January 2 it is evident that the principal feeder is a current of warm air flowing over the South Atlantic States, which curls into the closed isobars from the northward; here the cusp formation is somewhat obscure, and this usually happens while the center is so far to the south. On January 7 the main stream feeds into

the vortex from the northwest, and on the western and southern sides, where the isobars are dense, the stream curls into the center. On February 27 there is a strong stream from the southeast and another from the northwest, both of which curl strongly into the central vortex.

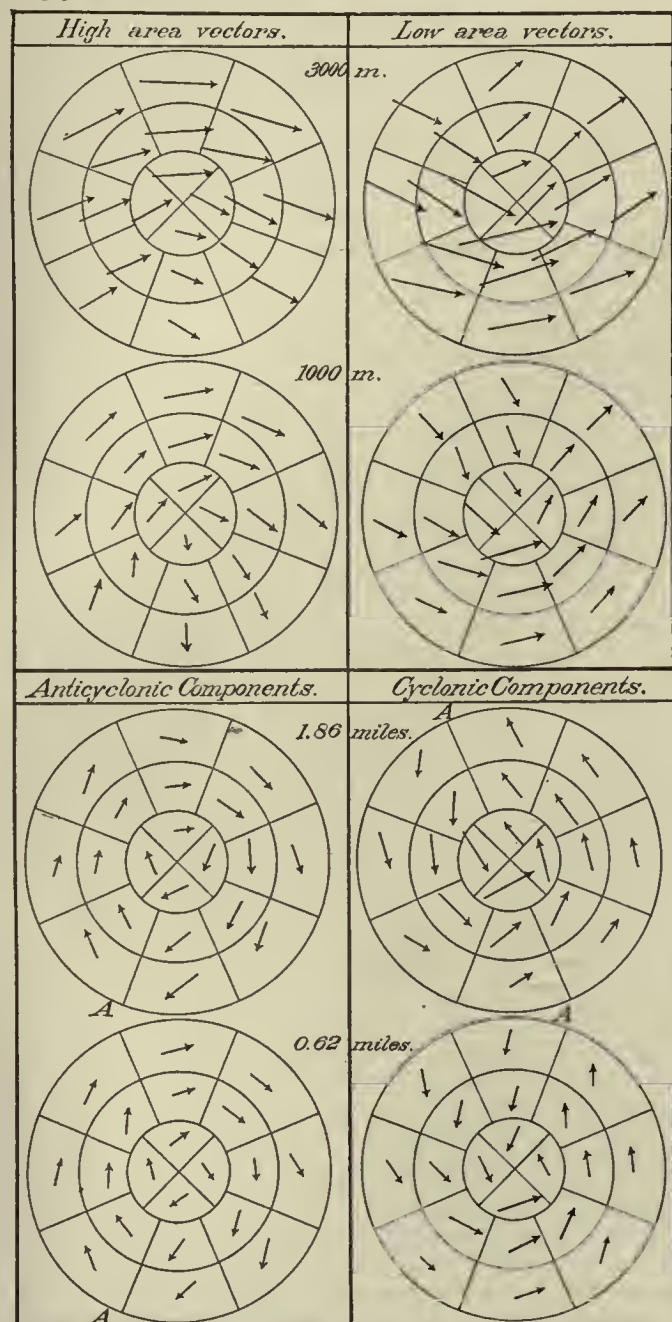


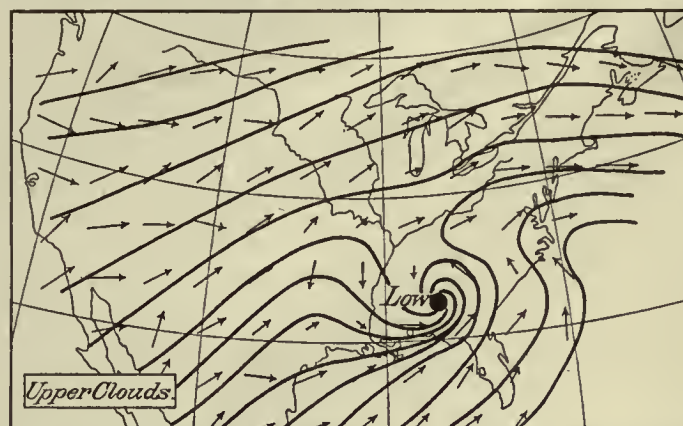
FIG. 26.—The vectors of motion and their components in anticyclones and cyclones at the 1000-mile and 3000-mile levels.

It should be particularly noted that the stream curls into the central vortex at all levels from the ground upward, crossing the closed isobars at some angle, but running parallel to the open isobars, thus confirming the results of the Cloud Report.

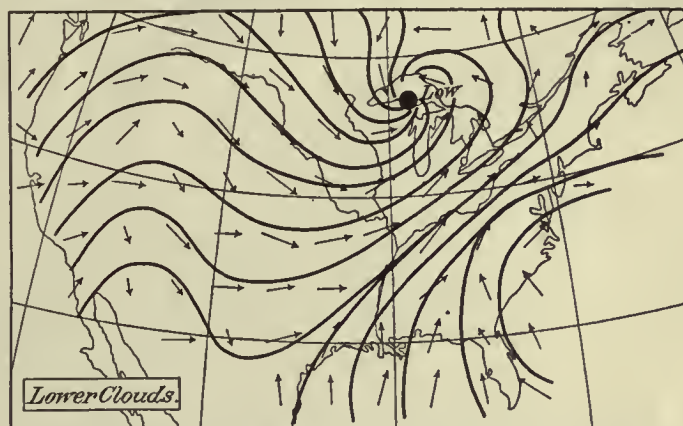
It should be observed, also, that the U-shaped opening in the northern cyclones is swung around to the northeastward, thus distorting the lines from their primary position of symmetry, which is toward the pole. This is due to the fact that the cyclone has vertical and gyratory components which penetrate from lower to higher levels, and therefore into the upper layers, drifting more rapidly eastward than the lower.

BIG—5

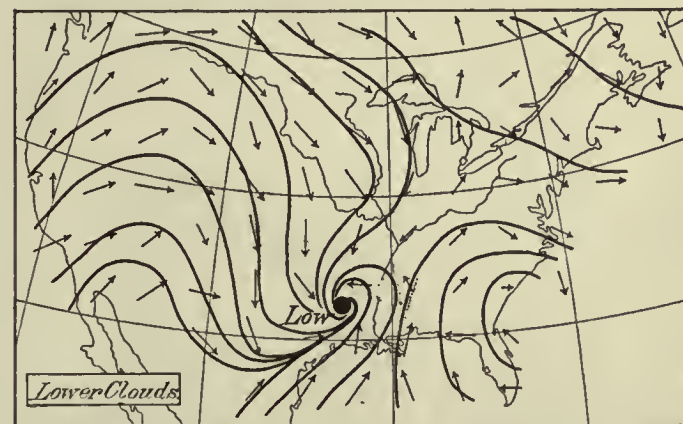
Such distortion is accompanied by an interchange of the inertia of motion, and this is the part of the thermal machine of the atmospheric circulation which acts as a brake upon the swiftly flowing eastward drift. This is the means by which the eastward velocities are slowed down from the excessive



III.—Summer hurricane low. Chart 35, International Cloud Report.



II.—Winter west Gulf low. Chart 29, International Cloud Report.



I.—Winter Lake region low. Chart 23, International Cloud Report.

FIG. 27.—The stream lines at cumulus levels for cyclones and at cirrus levels for hurricanes.

motions required, in the general theory by the law of the preservation of vortex areas, into the moderate motions actually observed. Since this penetrating power may extend to the cirrus levels, the total energy of retardation is evidently very great, and therefore this portion of the problem of the general circulation should be developed on the lines already outlined in my papers, rather than on those followed by Professor Ferrel. Furthermore, we remark that my construction is not in accord with the theory of the German vortex, as also explained in that

report. This vortex requires a local center of heat and a vertical current, with zero velocity at the center and maximum velocity at a circle on the edge of the closed curves, from which locus it gradually falls away to zero again at a considerable distance. In nature we have, on the other hand, individual stream lines of different temperatures curling into a common center, with velocity increasing up to the very center, as indicated on Chart 69 of the Cloud Report. The German vortex is much nearer the natural type than the Ferrel vortex, but there are features in it which are not compatible with the observations themselves. The disturbance of the eastward drift by the penetration of a cyclonic vortex into the upper strata is further illustrated by the scheme of fig. 28, where the successive levels are

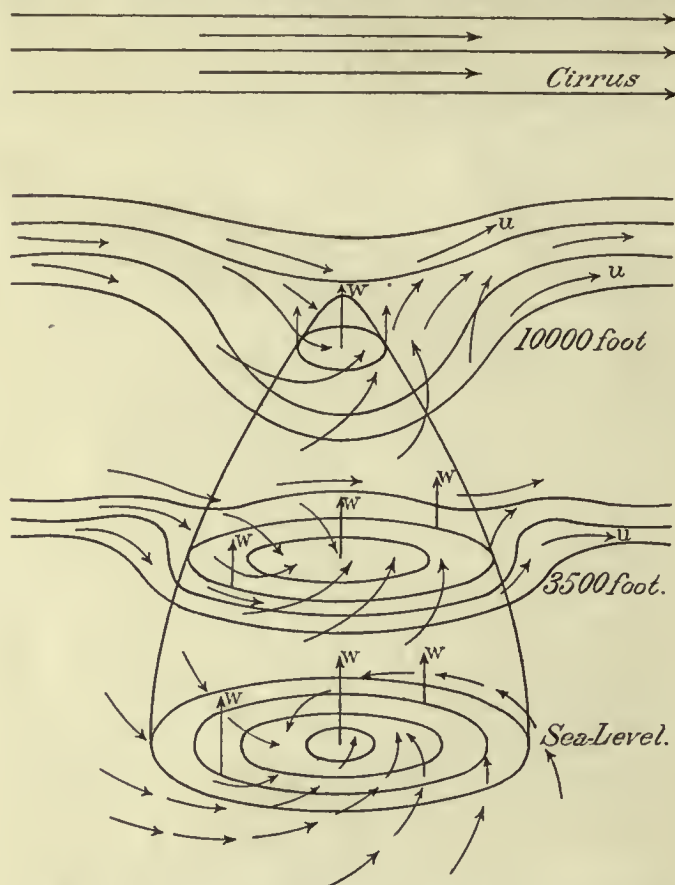


FIG. 28.—Scheme of the disturbance of the eastward drift by the penetration of a cyclone vortex into the upper strata.

shown with the isobars bending away from their normal eastward direction, first into U-shaped curves about the axis, then to cusps and closed curves, and finally to simple closed curves at the surface. These closed curves always imply a vortex with its vertical component governed by the usual vortex laws. The boundary of the true vortex action diminishes in size, and loses itself in the upper strata as a simple sinuous deflection. The vortex throws up a vertical component all over its area in proportion to the gyratory velocity, and in the center this forms a rising current, continuous and undisturbed, till high levels are attained. On the edges, however, the vertical component is stripped off by the action of the eastward drift, which also acts more powerfully in proportion to the elevation. This depletion of the surface of the vortex in proportion to the height is the mechanical mode that controls the escape of the upward current, which loses itself to the eastward by merging in the general circulation, whence it passes through other anticyclones and cyclones in succession. The radial horizontal component is inward toward the center in all levels of the cyclone, as was indicated in my Cloud Report. Thus, the en-

tire complex of the circulation has dynamic components, and the energy thus expended must be referred back finally to the source of heat in the Tropics, where the absorption of radiant energy from the sun goes on vigorously at the surface of the earth. The great general cyclone is perpetuated by the vertical uplift of the strata, due to the residue of the tropical heat which does not leak out toward the poles in horizontal warm currents of air near the surface, and its motion is in general nearly independent of the counterflow of these lower currents, except for the distortion due to the penetration just described. We have therefore established the existence in the cyclone of the interaction of three practically independent currents of air, (1) the great overflowing eastward drift, (2) the underflowing cold current from the northwest, and (3) the underflowing warm stream from the south.

THE INTERACTION OF THE THREE THERMAL CURRENTS.

It is necessary yet further to consider the thermal action of these currents which have very different temperatures. For it is evident that the formation of local closed isobars with vortex action and vertical currents, while accompanied by dynamic forces must yet depend upon a powerful and persistent thermal source. We have elsewhere shown that this energy is not to any great extent the latent heat of condensation of aqueous vapor, this being a secondary product; nor is the effect purely dynamic as the eddy theory implies. Where, then, shall we find a true efficient source of heat that is competent to account for all the conditions observed in the circulation phenomena of the atmosphere. It seems to me that this is to be attributed to the *thermal action due to the overflow of layers of cold air upon masses of warm air*. Abnormal stratification of air currents, where the relatively cold is above the warm, necessarily involves an upward current having an energy proportional to the difference of temperature. It is not necessary to say more about the truth of the view that this stratification exists, because such an overflow is really one of the most common conditions to be observed in meteorology. If a warm current leaves the latitudes of the high pressure belt, 35° more or less, and runs northward, it begins to underflow the eastward drift. If a cold area slides down from the northwest into warm latitudes, its upper portions are drifted forward over the warm lower strata. If two currents counterflow together the cold western masses are drifted forward upon the warmer at moderate levels, also warm masses are carried eastward over the next anticyclonic area. The instant the normal thermal equilibrium of the atmosphere is disturbed by such stratifications, thermal energy is present for the formation of dynamic vortices. Thus a hurricane begins in the late summer when the sun retreating southward brings the first layers of cool air to overspread the Tropics in a sheet. The warm surface air then begins to flow under this and penetrates it in a vortex, and this continues to operate as long as the flow of current sheets of two temperatures from the different sources continues. The track of a hurricane can thus traverse thousands of miles, because the cold overflow sheet covers the temperate zone, and the warm underflow current is directed in streams depending upon the general circulation of the lower air about the permanent anticyclonic centers of action. A specific example will make these remarks more definite.

In the Cloud Report we took great pains to construct the abnormal gradients of pressure, temperature, and vapor tension, such as are observed when the cumulus clouds are in the process of formation. These gradients are to be found in Tables 147, I to VII, for the metric system, and in Tables 153, I to VII, for the English system. By entering these tables with the prescribed arguments we can find the gradients which are prevailing at a given level in a cyclonic circulation. These tables are constructed primarily in reference to the 3500-foot

plane, but they can be extended to other levels by the adjoining precepts, if some judgment is exercised. Furthermore, it was essential to establish the normal conditions which prevail in the atmosphere at two higher planes, so that the difference between the normal gradients, which may be readily computed from the mean monthly values as given in the Barometry Report, and the abnormal gradients, which pertain to the different subareas of cyclones and anticyclones, may be obtained. This was one of the purposes that was kept in mind in constructing the Barometry Report, and the data for such normal gradients are given in Table 48. By subtracting the numerical values for B , t , e , on the different planes, and dividing by the difference in elevation, these normal gradients are found. By using the surface data in connection with the three selected planes, we obtain several systems of gradients which can thus be computed for mutual comparison. As to the abnormal gradients of temperature, for example, we may take from Table 153, II, of the Cloud Report, the values for the different subareas in a cyclone, the table being quoted only in part.

TABLE 1.—Pressure and temperature gradients in English measures.
FALL OF PRESSURE IN INCHES PER 100 FEET.

$\frac{e}{B}$	.0100	.0120	.0140	.0160	.0180	.0200	.0220	.0240
t ° F.								
90			0.095	0.095	0.095	0.096	0.096	0.097
80		0.096	.097	.097	.097	.097	.098	.099
70	0.098	.099	.100	.100	.101	.102	.102	.103
60	.102	.103	.104	.104	.105	.106	.107	.108
50	.105	.106	.107	.107	.108	.109	.110	
40	.107	.108	.109	.109	.110	.111		
30	.109	.110	.111	.111	.112			
20	.113	.114	.115	.115				
10	.117	.118						
0	.120							

FALL OF TEMPERATURE IN DEGREES PER 100 FEET.

$\frac{e}{B}$	.0100	.0120	.0140	.0160	.0180	.0200	.0220	.0240
t ° F.								
90					0.88	0.82	0.74	0.240
80		0.85	0.82	0.74	.65	.58	.52	.47
70	0.79	.68	.59	.51	.43	.37	.34	.31
60	.59	.48	.40	.33	.30	.28	.27	
50	.41	.33	.25	.20				
40	.26							

From Table 153, International Cloud Report.

In the eastern subareas we have high temperatures and high vapor tensions (t_1, e_1) so that the temperature gradients are large; in the western areas the temperatures and also the vapor tensions are lower (t_2, e_2). Then (t_1, e_1) will give larger values of G . t_1 than (t_2, e_2) will give for G . t_2 . If the G . t_1 exceeds the normal gradient of the season, we have the mechanical cause for a vertical current. This principle can be applied throughout the cyclonic field with unflinching results of the right kind. In general it may be stated that the normal temperature gradients are about three-fifths the adiabatic rate, and this occurs when the strata are in atmospheric equilibrium and no currents are distinctly rising or falling. In cyclones and anticyclones, where the vertical currents are pronounced, the temperature gradients are about the same as the adiabatic rate. This remarkable theorem regarding gradients is very significant in the physical thermodynamics of the atmosphere. Hence, we conclude that air is rising to the east, but falling to the west of the center of the cyclone. It seems almost a paradox that in the warm current of air the air should be rising to a region where the pressure is higher than it was before the movement began. But rising air always increases the

pressure in the stratum to which it is moving, and this hardly needs to be reaffirmed. The overflowing cold air in the strato-cumulus level, therefore, in itself generates the power which raises the warm air underneath it by the usual thermodynamic laws. Hence, if a relatively cold layer is thrust into a column of air otherwise normally disposed, the warm lower layers will rise to meet the cold stratum, and the higher strata which are also relatively warm will fall toward it. Relatively warm air flows to the place of relatively cold air. If the surface layers are cooled by radiation in anticyclones the air of the upper strata will settle down upon them by this law, namely, that relatively warm air seeks relatively cold air. The currents of transfer thus set up have an adiabatic system of gradients; on the other hand, the normal layers of the atmosphere do not dispose themselves into adiabatic strata, as was proved in my Cloud Report. Some specific examples of the operation of these processes will now be mentioned.

EXAMPLES OF THE INTERACTION OF ABNORMALLY COLD AND WARM STRATA.

A survey of the conditions prevailing at the time of the waterspout photographed on August 19, 1896, off Cottage City, in Vineyard Sound, Mass., leads me to the results contained in Table 2, extracted from a report now in preparation on this important phenomenon. It contains for the $\alpha, \beta, \gamma, \delta$ stages the heights on the photograph in millimeters and inches, the actual height in meters and feet, and the pressure, temperature, and vapor tension at the beginning and end of each stage. Thence the gradients are found per 100 meters, or per 100 feet, viz: (1) (G_o) Observed, according to the actual observations, (2) (G_c) Cloud, according to the Cloud Report Tables 147 and 153, and (3) (G_b) Barometry, the normal gradient prevailing in the air for that month as deduced from Table 48 of the Barometry Report. This waterspout was formed under remarkable conditions. The pressure was a little high, 30.05 inches; the temperature was exactly normal for the month of August, 67.5° F., and the vapor tension was low, corresponding to a relative humidity of 64 per cent. This gives the ratio $\frac{e}{B} = 0.0143$ from which the gradients (G_c), cloud, were obtained.

Comparing (G_o), (G_c), and (G_b) we note that (G_b) is less than (G_o) and (G_c) in both the pressure and the temperature, but greater in the vapor tension for both the α and β stages. This waterspout was formed in a congested region on the southeast edge of a great area of high pressure, which was pushing over the New England coast line at that time, and there was no cyclonic action of any kind. There was then generated a rapid formation of cumulo-nimbus clouds, with rainfall at the front, waterspouts in the middle, and thunderstorms with hail following, all in the course of a couple of hours. I conceive that this entire set of phenomena was due to the drifting forward (in the strato-cumulus level) of the relatively cold air of the anticyclone as a sheet overspreading the quiet layers of relatively warm air resting on the ocean. The normal temperature at the ocean level is 67.7° F. for August, and 60.4° at the 3500-foot level. But by computation the temperature was 48.7° at that level, giving an abnormal fall of 11.7° F., due to the overflowing of the cold stratum from the advancing anticyclone. This great fall in temperature was not caused by any change in the surface conditions, which remained normal till the thunderstorm following the rain and waterspouts brought the cold air to the surface and caused the temperature to fall at the ocean also. The cold upper stratum evidently preceded the surface cold air by several hours, and this is typical of the conditions frequently prevailing in similar local congested circulations of the lower strata, where abnormal stratification and so-called inversion of temperature is observed. This abnormal stratification of cold over warm layers caused the

TABLE 2.—Summary of the data for the Cottage City waterspout, August 19, 1896.

Stages.	Metric system.					English system.					
	H. photo.	Height.	B.	t.	e.	H. photo.	Height.	B.	t.	e.	
	<i>Mm.</i> 176.4	<i>Meters.</i> 4,942	<i>Mm.</i> 414.5	<i>°C.</i> —12.0	<i>Mm.</i> 1.64	<i>Inches.</i> 6.95	<i>Feet.</i> 16,214	<i>Inches.</i> 16.32	<i>°F.</i> 10.4	<i>Inch.</i> 0.065	
δ -stage	73.6	2,062	{ —6.04 —6.50	{ —0.582 —0.550	{ —0.142 —0.140	2.90	6,765	{ —0.072 —0.078	{ —0.319 —0.302	{ —0.00170 —0.00168	(G_o) Observed. (G_c) Cloud.
	102.8	2,880	539.0	0	4.57	4.05	9,449	21.22	32.0	0.180	
γ -stage	2.6	74	—6.76	.....	.....	0.10	243	—0.082	.....	.....
β -stage	100.2	2,806	544.0	0	4.57	3.95	9,206	21.42	32.0	0.180	
	61.7	1,728	{ —7.40 —7.60 —7.11	{ —0.538 —0.540 —0.376	{ —0.240 —0.260 —0.364	2.43	5,669	{ —0.089 —0.091 —0.085	{ —0.294 —0.294 —0.207	{ —0.00288 —0.00312 —0.00437	(G_o) Observed. (G_c) Cloud. (G_b) Barometry.
	38.5	1,078	672.0	9.3	8.72	1.52	3,537	26.46	48.7	0.343	
α -stage	38.5	1,078	{ —8.46 —8.40 —8.24	{ —0.963 —0.950 —0.375	{ —0.204 —0.192 —0.296	1.52	3,537	{ —0.101 —0.101 —0.098	{ —0.531 —0.522 —0.206	{ —0.00246 —0.00230 —0.00355	(G_o) Observed. (G_c) Cloud. (G_b) Barometry.
Sea level ..	0	0	763.27	19.72	10.92	0	0	30.05	67.5	0.430	

thermal difference necessary to enable the hydrostatic pressure of the neighboring region to cause a vertical current. In this rising air the temperature and pressure gradients changed from the normal rates prevailing previous to the sudden change into adiabatic rates, which seem to have been fully reached in the temperature. There are numerous physical functions useful in meteorology involved in these data, and it will be valuable to compute the B , t , e in the higher strata for as many instances of the kind as is practicable.

Some idea of the energy available to produce a vertical current can be gained from the following consideration: The normal temperature gradient in the α -stage is -0.206 per 100 feet, the observed gradient is -0.531 , and this is a gain of -0.325 . The normal pressure gradient is -0.098 per 100 feet, the observed gradient is -0.101 , and the gain is -0.003 per 100 feet, or 0.106 inch in the α -stage. That would be equivalent to the enormous gradient of -13.5 inches in a degree, 111,111 meters, along the surface of the earth, which is 100 times as great as that observed for the usual horizontal gradients. In the β -stage the temperature normal gradient is -0.207 , the observed is -0.294 , the increase -0.087 per 100 feet. Comparing this with -0.325 , the increase in the α -stage, we conclude that the efficient buoyancy gradient is four times greater in the α -stage than in the β -stage. This is contrary to what should be expected if the buoyancy is chiefly due to the condensation of aqueous vapor to water in the cloud or β -stage, but it is in accord with the theory of stratification proposed in this paper.

We have other examples of the effect of an overflow of a cold stratum upon the warm air of lower levels in the numerous cases where anticyclonic areas advance into the central valleys from the northwest without a cyclonic development in front of them. There is produced in such conditions a wide band of rainfall on the map, stretching from the Lake region to the Gulf of Mexico, where no dynamic action is operating which can raise the air mechanically. The cold, overflowing sheet will, however, cause an increase in the temperature gradient, and this is accompanied by rising air and precipitation over immense areas of country. In certain cases the anti-

cyclonic area will advance to the Atlantic coast before causing such ascending currents, and then a powerful small cyclone sometimes develops suddenly near the coast of New Jersey or Virginia, and as this advances to New England it produces hurricane winds. When two currents of different temperatures flow together in the Mississippi Valley the overflow of the cold layers from the northwest upon the warm layers from the south produces a congested condition, accompanied by thunderstorms, tornadoes, and general violent local circulations in the southeastern quadrants of the cyclone. On the other hand, the wide range in temperature required to cause such rapid vertical circulations may also be produced by simply overheating the surface layers relatively to the upper strata. This is the case in summer, when in anticyclonic areas the solar radiation passes through all the upper layers to the surface without heating them sensibly. Then the earth's radiation, in its turn, does have the power to overheat the lower strata, and this causes an increased temperature gradient relatively to the cumulus levels, which is the atmospheric condition for numerous summer thunderstorms and desert sand squalls. In the winter the areas of low pressure over the northern portions of the Atlantic and Pacific oceans are due to the relatively high temperature of the ocean waters and adjacent air layers. During the months in which the lower layers are too warm in comparison with the adjacent continental areas and with the strata above them, the well-known permanent cyclones prevail. The reverse case occurs in summer over the ocean belts at the boundary of the tropical and the temperate zones, where the water holds the surface strata at temperatures lower than is required for equilibrium, and so causes a settling down of the upper air. This is, of course, an effect which increases the usual dynamic action produced by the general circulation in this high pressure belt.


In the autumn the cold layers advance from the northern zones into the Tropics, first in the higher strata which over-spread the warm and moist air of the doldrums. This causes an increase of the vertical temperature gradient, and a hurricane or large columnar vortex is formed, through whose structure the warm air pours upward to great heights, and enables this con-

figuration in some cases to perpetuate itself by such convection for many days. It is the wide spread cold sheet of the upper strata which is the persistent source of energy in a hurricane, and also in a cyclone. The advancing movement of the center is due to the fact that the warm air, which lies to the eastward, promptly rises to meet the overflowing cold sheet, the two mutually sustaining each other's action. The downflow of the cold air on the western side is simultaneous with the upflow on the eastern side, but the deficiency of pressure on one side and the excess of it on the other by its continuous operation causes the entire structure to advance. In addition to this, the drift of the upper strata, eastward in the temperate zone and westward in the Tropics, carries along the cyclone, which adheres to them by the interactions that have been described.

GENERAL RESULTS STATED.

The results of this research may be summed up briefly as follows: (1) The cyclone is not formed from the energy of the latent heat of condensation, however much this may strengthen its intensity; it is not an eddy in the eastward drift; but it is caused by the counterflow and overflow of currents of different temperatures. Ferrel's canal theory of the general circulation is not sustained by the observations, nor is his theory of local cyclones and anticyclones tenable. There are difficulties with regard to the German vortex theory, but this is nearer the truth than the Ferrel vortex. The structure in nature is

actually more complex than has been admitted in these theoretical discussions, but it doubtless can be worked out successfully along the lines herein indicated. (2) Regarding the relation of the upper level isobars to practical forecasting, it is noted as the result of the examination of the charts of December, 1902, January and February, 1903, that (a) the direction of the advance of the center of the low pressure is controlled by the upper strata, and its track for the following twenty-four hours is usually indicated by the position of the 10,000-foot level isobars; (b) The velocity of the daily motion is also dependent upon and is shown by the density of these high level isobars; (c) the penetrating power of the cyclone is safely inferred from an inspection of the three maps of isobars of the same date; (d) there is decided evidence that areas of precipitation occur where the 3500-foot isobars and the 10,000-foot isobars cross each other at an angle in the neighborhood of 90°; (e) there have been several cases in which the formation of a new cyclone has been first distinctly shown on the upper system of isobars before penetrating to the surface or making itself evident at the sea level. (3) It is expected that by completing our discussion of the temperature gradients between the surface and the higher levels we shall be able to secure daily isotherms as well as daily isobars on the upper planes, and this will tend to strengthen any further examination of these important problems. A suitable report will be prepared in which the data now coming into our possession will be subjected to a mathematical analysis and discussion.

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